

A MULTI-WAVELENGTH STUDY OF LOW REDSHIFT CLUSTERS OF GALAXIES I. COMPARISON OF X-RAY AND MID-INFRARED SELECTED AGNs

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ABSTRACT

Clusters of galaxies have long been used as laboratories for the study of galaxy evolution, but despite intense, recent interest in feedback between AGNs and their hosts, the impact of environment on these relationships remains poorly constrained. We present results from a study of AGNs and their host galaxies found in low-redshift galaxy clusters. We fit model spectral energy distributions (SEDs) to the combined visible and mid-infrared (MIR) photometry of cluster members and use these model SEDs to determine stellar masses and star-formation rates (SFRs). We identify two populations of AGNs, the first based on their X-ray luminosities (X-ray AGNs) and the second based on the presence of a significant AGN component in their model SEDs (IR AGNs). We find that the two AGN populations are nearly disjoint; only 8 out of 44 AGNs are identified with both techniques. We further find that IR AGNs are hosted by galaxies with similar masses and SFRs but higher specific SFRs (sSFRs) than X-ray AGN hosts. The relationship between AGN accretion and host star-formation in cluster AGN hosts shows no significant difference compared to the relationship between field AGNs and their hosts. The projected radial distributions of both AGN populations are consistent with the distribution of other cluster members. We argue that the apparent dichotomy between X-ray and IR AGNs can be understood as a combination of differing extinction due to cold gas in the host galaxies of the two classes of AGNs and the presence of weak star-formation in X-ray AGN hosts.

Subject headings: galaxies:active, galaxies:clusters:general, infrared radiation, X-rays

1. INTRODUCTION

Galaxy formation and evolution has long been a subject of considerable interest, with early work dedicated to exploring the physical processes responsible for star-formation (Whipple 1946), explaining the genesis of the Milky Way (Eggen et al. 1962), and examining the evolution of galaxies in clusters (Spitzer & Baade 1951). Models for the evolution of galaxies in clusters gained strong observational constraints with the discovery of an apparent evolutionary sequence among local clusters (Oemler 1974). The discovery that the fraction of blue, spiral galaxies in relaxed galaxy clusters increases from $z = 0$ to $z \approx 0.4$ quickly followed (Butcher & Oemler 1978, 1984). The dearth of spiral galaxies in the high-density regions at the centers of galaxy clusters is known as the morphology-density relation (Dressler 1980; Postman & Geller 1984; Dressler et al. 1997; Postman et al. 2005). This relation places additional, strong constraints on evolutionary models for cluster galaxies. That star-forming galaxies are also rare in the centers of clusters had been previously suggested by the results of Osterbrock (1960) and was subsequently observed in other work (Gisler 1978; Dressler et al. 1985). The impact of environment on the frequency and intensity of star-formation at a wide variety of density scales has been measured using numerous visible (Abraham et al. 1996; Balogh et al. 1997; Kauffmann et al. 2004; Poggianti et al. 2006, 2008;

von der Linden et al. 2010) and mid-infrared (MIR; Saintonge et al. 2008; Bai et al. 2009) diagnostics. Star-forming galaxies are consistently found to be more common and to have higher star-formation rates (SFRs) in lower density environments and at higher redshift (Kauffmann et al. 2004; Poggianti et al. 2006, 2008).

The observed trends in star-formation with environment are usually attributed to variations in the sizes of gas reservoirs, either the existing cold gas or the hot gas that can cool to replenish the cold gas as it is consumed. Given that AGNs also consume cold gas to fuel their luminosity, similar patterns might be expected among AGNs. Indeed, recent work reveals strong dependencies of the luminosities and types of AGNs on environment (e.g. Kauffmann et al. 2004; Popesso & Biviano 2006; Constantin et al. 2008; Montero-Dorta et al. 2009) for AGNs selected via visible-wavelength emission-line diagnostics. Von der Linden et al. (2010) find fewer “weak AGNs” (primarily LINERS) among red sequence galaxies near the centers of clusters compared to the field, but they find no corresponding dependence among blue galaxies. Intriguingly, while Montero-Dorta et al. (2009) independently report a decline in the fraction of low-luminosity AGNs toward the centers of low-redshift clusters, they find an *increase* in the fraction of LINERS in higher density environments. The difference is likely a result of evolution. Montero-Dorta et al. (2009) found qualitatively different behavior between their main $z \sim 1$ sample and the result produced when they applied their analysis to SDSS clusters. These results indicate

that the variation of galaxy properties with local environment may influence the types of AGNs observed and that evolution in the relationship between some AGN classes and their host galaxies is important. Understanding the environmental mechanism that transforms star-forming galaxies into passive galaxies in clusters may help relate gas reservoirs in cluster galaxies to galaxy evolution as well as to AGN feeding and feedback.

Several mechanisms to cause the transformation from star-forming to passive galaxies have been proposed. These include ram-pressure stripping of cold gas (Gunn & Gott 1972; Quilis et al. 2000; Roediger & Hensler 2005), strangulation (Larson et al. 1980; Balogh et al. 2000; Kawata & Mulchaey 2008; McCarthy et al. 2008) and galaxy harassment (Moore et al. 1996, 1998; Lake et al. 1998). Each mechanism operates on a different characteristic timescale and has its greatest impact on galaxies of different masses and at different radii. In principle, the transition of galaxy populations from star-forming to passive as a function of environment can probe the relative importance of these processes. However, such approaches suffer from practical difficulties. For example, Bai et al. (2009) argue that the similarity of the $24\mu\text{m}$ luminosity functions observed in galaxy clusters and in the field suggests that the transition from star-formation to quiescence must be rapid, which implies that ram pressure stripping must be the dominant mechanism. Von der Linden et al. (2010), by contrast, find a significant trend of increasing star-formation with radius up to $5R_{200}$ from cluster centers. They conclude that preprocessing at the group scale is important, which is inconsistent with ram pressure stripping as the driver of the SFR-density relation. Patel et al. (2009) find a similar trend for increasing average SFR with decreasing local density down to group-scale densities ($\Sigma_{gal} \approx 1.0 \text{ Mpc}^{-2}$) near RX J0152.7-1357 ($z = 0.83$). The importance of preprocessing in group-scale environments reported by these authors suggests that strangulation rather than ram pressure stripping drives the SFR-density relation. The starkly different conclusions reached by Bai et al. (2009) compared to Patel et al. (2009) and von der Linden et al. (2010), despite their common use of star-forming galaxies to examine the influence of environment, highlight the difficulties inherent in such studies.

Attempts to distinguish between various environmental processes become still more difficult with cluster samples that span a wide range in redshifts. The epoch of cluster assembly ($0 \leq z \lesssim 1.5$, e.g. Berrier et al. 2009) coincides with the epoch of rapidly declining star formation (e.g. Madau et al. 1998; Hopkins & Beacom 2006) and AGN activity (e.g. Shaver et al. 1996; Boyle & Terlevich 1998; Shankar et al. 2009), which makes it difficult to disentangle rapid environmental effects from the global reduction in the amount of available cold gas. Dressler & Gunn (1983) found early evidence for an increase in AGN activity with redshift, and the Butcher-Oemler effect had already provided evidence for a corresponding increase in SFRs. In the last decade, the proliferation of observations of high-redshift galaxy clusters at X-ray, visible and infrared wavelengths has yielded similar trends in the fraction of both AGNs (Eastman et al. 2007; Martini et al. 2009)

and star-forming galaxies (Poggianti et al. 2006, 2008; Saintonge et al. 2008; Haines et al. 2009) identified using a variety of methods. These newer results have also examined cluster members confirmed from spectroscopic redshifts rather than relying solely on statistical excesses in cluster fields, which permits more detailed study of the relationships between galaxies and their parent clusters.

The wide variety of AGN selection techniques employed in more recent studies represents an important step forward in understanding the dependence of AGNs on environment. Several recent papers have used X-rays to study the frequency and distribution of AGNs in galaxy clusters (Martini et al. 2006, henceforth M06; Martini et al. 2007; Sivakoff et al. 2008; Arnold et al. 2009; Hart et al. 2009) and their evolution with redshift (Eastman et al. 2007; Martini et al. 2009). Martini et al. (2009) found that the AGN fraction among cluster members increases with decreasing local density and increases dramatically ($f_{AGN} \propto (1+z)^{5.3 \pm 1.7}$) with redshift. They also found that X-ray identification produces a much larger AGN sample than visible-wavelength emission line diagnostics: only 4 of the 35 X-ray sources identified as AGNs by M06 would be classified as AGNs from their visible-wavelength emission lines. Similar results have been found when comparing radio, X-ray and mid-IR AGN selection techniques for field AGNs (e.g. Hickox et al. 2009).

The different AGN selection techniques identify different AGN populations and suffer from distinctive selection biases. Both X-ray and visible-wavelength techniques can miss AGNs due to absorption, either in the host galaxy or in the AGN itself; however, X-ray selection can find lower luminosity AGNs and AGNs behind larger absorbing columns compared to emission line selection. Mid-infrared selection techniques suffer from relatively poor angular resolution, so they are mainly sensitive to AGNs that outshine their host galaxies in the band(s) used to perform the AGN selection. The X-ray and visible techniques can also be contaminated by emission from the host galaxy. While the identification of X-ray sources with $L_X > 10^{42} \text{ erg s}^{-1}$ as AGNs is unambiguous, X-ray luminosities in the 10^{40} – $10^{42} \text{ erg s}^{-1}$ range can be produced by low-mass X-ray binaries (LMXBs), high-mass X-ray binaries (HMXBs), and thermal emission from hot gas. Both visible-wavelength and MIR indicators are subject to contamination from young stars, which produce emission lines and heat dust near star-forming regions until it emits in the MIR. Even the interpretation of the well-established Baldwin-Phillips-Terlevich diagram (Baldwin et al. 1981) can be controversial in the transition region between star-forming galaxies and AGNs.

These difficulties motivate the use of multiple techniques to obtain a complete census of AGN and to correctly identify potential imposters. In this paper, we extend the work of Martini et al. (2006, 2007) by supplementing their X-ray imaging and visible-wavelength photometry with MIR observations from the Spitzer Space Telescope. We use these data to select AGNs independent of their X-ray emission. We also measure the properties of AGN host galaxies by fitting their visible to MIR spectral energy distributions (SEDs). We discuss our visible and MIR data reduction and photometry in Section 2. Section 3 details our techniques for identifying AGNs and measuring galaxy properties, and we describe

the results in Section 4. We discuss the implications for the relationship between AGNs and their host galaxies in Section 5. Throughout this paper we use the WMAP 5-year cosmology—a Λ CDM universe with $\Omega_m = 0.26$, $\Omega_\Lambda = 0.74$ and $h = 0.72$ (Dunkley et al. 2009).

2. OBSERVATIONS & DATA REDUCTION

We obtained MIR observations with the *Spitzer* Space Telescope of the X-ray sources identified as members of 8 low-redshift galaxy clusters by M06. The initial reduction of the *Spitzer* imaging is described in Section 2.1. Visible wavelength photometry of these clusters were obtained at the 2.5m du Pont telescope at Las Campanas by M06. We provide a brief summary of these data in Section 2.2; further details are provided by M06. We then discuss the corrections for Galactic extinction and for instrumental effects in Section 2.3.

2.1. *Spitzer* Reduction

We obtained mid-infrared (MIR) observations from the *Spitzer* Space Telescope using the IRAC ($\lambda_{eff} = 3.6, 4.5, 5.8, 8.0 \mu m$; Fazio et al. 2004) and MIPS ($\lambda_{eff} = 24$; Rieke et al. 2004) instruments from *Spitzer* program 50096 (P.I. Martini). Observations were carried out between 2008 November 1 and 2009 April 22. *Spitzer* pointings were chosen to image the X-ray point sources in 8 low-redshift galaxy clusters identified by M06. We supplemented these observations with data from the *Spitzer* archive for Abell 1689 and AC 114.

Spitzer’s cryogen ran out before the MIPS observations of three clusters (Abell 644, Abell 1689 and MS 1008.1-1224) were carried out. In one of these clusters (Abell 1689) we extended our coverage to $24 \mu m$ using observations from the *Spitzer* archive, leaving two clusters with no usable MIPS observations. The Astronomical Observation Request (AOR) numbers used to construct the MIR mosaic images of each cluster are listed in Table 1, along with the corresponding 3σ observed-frame luminosity limits at both 8 and $24 \mu m$. These limits are approximate because the image depth varies across the mosaics due the changing number of overlapping pointings. Quoted limits correspond to areas with “full coverage” but without overlap from adjacent pointings.

The raw *Spitzer* data are reduced by an automated pipeline before they are delivered to the user, but artifacts inevitably remain in the calibrated (BCD) images. Preliminary artifact mitigation for the IRAC images was performed using the IRAC artifact mitigation tool by Sean Carey¹. We inspected each corrected image after this step and determined whether the image was immediately usable, if additional corrections were required, or if it simply had too many remaining artifacts to be reliably corrected. The latter class primarily included images with extremely bright stars that caused artifacts too severe to be corrected. Where appropriate, additional corrections were applied using the muxstripe² and jailbar³ correctors by Jason Surace and the column pull-

down corrector⁴ by Leonidas Moustakas. Artifacts in the MIPS images were removed by applying a flatfield correction algorithm packaged with the *Spitzer* mosaic software, (MOPEX⁵), as described on the *Spitzer* Science Center (SSC) website⁶.

Mosaic images for both IRAC and MIPS were constructed from the artifact-corrected images using MOPEX. Aperture photometry was extracted from the resulting mosaics using the *apphot* package in IRAF. We converted the measured fluxes to magnitudes in the Vega system after the photometric corrections described in Section 2.3 had been applied. All magnitudes quoted in this work, both visible and MIR, are calculated with respect to the Vega standard. The photometric apertures used by *apphot* were chosen to enclose a region of approximately 10 kpc projected radius at the redshift of each cluster. These large apertures yielded reduced S/N, but most cluster members were sufficiently bright that the uncertainties on the measured fluxes were dominated by systematic errors (5%) in the zero-point calibration, except at $24 \mu m$. The use of large photometric apertures also allowed galaxies to be treated as point sources for the purpose of computing aperture corrections, as recommended by the SSC. A smaller aperture could improve the S/N, but this gain would be outweighed by the systematic uncertainty introduced by the aperture corrections for the resulting flux measurements, as aperture corrections for IRAC extended sources remain highly uncertain (IRAC Instrument Handbook⁷).

2.2. Visible Photometry

All 8 clusters in our sample have *B*-, *V*- and *R*-band imaging, and 4 of the 8 have *I*-band imaging. We extracted separate source catalogs for each of these bands using Source Extractor (SExtractor, Bertin & Arnouts 1996) and merged the catalogs using the *R*-band image as the reference image for astrometry and total (Kron) magnitudes. We correct from aperture to total magnitudes without altering the colors from the aperture photometry by applying the *R*-band aperture corrections to all bands,

$$m_{Kron} = m_{Ap} - (R_{Ap} - R_{Kron}) \quad (1)$$

where m_{Ap} and m_{Kron} are the aperture and Kron-like magnitudes, respectively, for the band being corrected. Rather than taking the published photometry from M06, we used the redshift-dependent apertures assigned to each cluster as described in Section 2.1. This maintains consistency with our IRAC photometry and results in relatively small aperture corrections, typically ~ 0.1 mag.

SExtractor returns *R*-band positions that are good to within a fraction of an arcsecond. However, the positions of sources in IRAC and MIPS images are less precise due to the poorer angular resolution and larger pixel sizes in these bands. We selected the best astrometric matches to each *Spitzer* source from the objects identified by SExtractor within a specified search radius, θ .

⁴ <http://ssc.spitzer.caltech.edu/dataanalysistools/tools/contributed/irac/cpc/>

⁵ <http://ssc.spitzer.caltech.edu/dataanalysistools/tools/mopex/>

⁶ http://ssc.spitzer.caltech.edu/dataanalysistools/cookbook/23/#_Toc256425880

⁷ http://ssc.spitzer.caltech.edu/irac/iracinstrumenthandbook/IRAC_Instrument_Handbook.pdf

¹ http://spider.ipac.caltech.edu/staff/carey/irac_artifacts/

² <http://ssc.spitzer.caltech.edu/dataanalysistools/tools/contributed/irac/automuxstripe/>

³ <http://ssc.spitzer.caltech.edu/dataanalysistools/tools/contributed/irac/jailbar/>

To determine the best value of θ , we scrambled the RA of SExtractor sources and determined how many Spitzer sources were matched to a scrambled galaxy as a function of θ . We found the best balance between purity and completeness for $\theta \approx 1''.25$. This search radius yielded spurious matches for less than 2% of objects. The actual contamination of our catalog will be much lower, because a Spitzer object with a spurious match will usually be better matched to its “true” counterpart, which has a median match distance $d = 0''.4$. The images used to perform the matching do not suffer from substantial confusion, even in the cluster centers, so erroneous photometry due to overlapping sources is unlikely to present a problem. Further details of the visible image reduction were described by M06.

2.3. Photometric Corrections

We estimated the Galactic reddening toward each of the 8 clusters in our sample from the dust map of Schlegel et al. (1998) and calculated extinction corrections assuming $R_V = 3.1$ and the Cardelli et al. (1989) reddening law. The resolution of the Schlegel et al. (1998) dust map requires us to use a common extinction correction for all cluster members. However, Galactic cirrus is apparent in some of our images, so this assumption is not always appropriate. This leads to additional uncertainty associated with the extinction corrections, but the total (visual) extinction toward our clusters is typically less than 0.1 mags. The associated uncertainties are therefore small. For the clusters with the highest extinctions (Abell 2104 and 2163, with $A_V = 0.73$ and 1.1, respectively), variations in extinction across the cluster represent an important source of systematic uncertainty. We account for this by adopting a 10% uncertainty in all extinction corrections and propagating this uncertainty to the corrected magnitudes. In Abell 2163, for example, this corresponds to an uncertainty of 0.11 mags in the dereddened V -band magnitude.

The raw fluxes measured from the MIR mosaics must be corrected for various instrumental effects, including aperture, array-location and color corrections, as described in the IRAC and MIPS⁸ Instrument Handbooks. Aperture corrections are, in principle, required for all observations. In practice, even our smallest apertures ($\sim 7''$) are large enough that aperture corrections to visible-wavelength point sources are negligible. For MIR point sources, this is not the case. We apply aperture corrections from the IRAC Instrument Handbook appropriate for our redshift-dependent photometric apertures to the IRAC photometry. These corrections are not strictly appropriate due to the extended nature of our sources; however, we have chosen apertures that are large compared to the sources ($\sim 3\times$ larger than the FWHM of the largest galaxies, see Section 2.1). We therefore apply aperture corrections appropriate for point sources.

We determined aperture corrections appropriate for our MIPS images by averaging a theoretical point-source response function (PRF) from STinyTim⁹ with three bright, isolated point sources in the Abell 3125 and Abell

2104 mosaics. The PRFs of sources from the different clusters agree with one another and with the theoretical PRF to within a few percent over the range of aperture sizes relevant for our MIPS photometry. The dispersion between the individual PRFs at fixed aperture size provides an estimate of the uncertainty on the corrections and is included in the $24\mu\text{m}$ error budget. The MIPS images of the other clusters lack bright, isolated points sources with which to make a similar measurement, so we assume that the PRF appropriate for Abell 3125 and Abell 2104 gives reasonable aperture corrections for all clusters. This introduces some systematic error in our derived $24\mu\text{m}$ fluxes, but the agreement of the observed PRFs of point-sources identified in Abell 3125 and Abell 2104 with the theoretical PRF indicates that this uncertainty is small.

The flatfield corrections applied to IRAC images by the automated image reduction pipeline are based on observations of the zodiacal background light, which is uniform on the scale of the IRAC field of view. It is also extremely red compared to any normal astrophysical source. The combination of scattered light due to the extended nature of the source and the color of the source illuminating the detector for the flatfield images results in different gains for point-sources and extended sources. It also requires an effective bandpass correction that varies with position on the detector. These effects can be corrected by applying a standard array-location correction image to a single IRAC image. For a mosaic, the magnitude of the required correction is significantly reduced by adding dithered images with different corrections at a given position on the sky. However, the residual effect can be a few percent or more depending on the number of overlapping IRAC pointings. We construct an array-location correction mosaic by co-adding the correction image for a single IRAC pointing shifted to the positions of each dithered image in the science mosaic. We measure the required array-location corrections in the same apertures used to measure the IRAC fluxes.

The *Spitzer* image reduction pipeline assumes a flat power-law SED to convert electrons to incident fluxes. Astrophysical sources typically do not show flat SEDs and therefore require color corrections to determine the true flux at the effective wavelength of a given band. This is especially important in star-forming galaxies, which show strong polycyclic aromatic hydrocarbon (PAH) emission features at 6.2 and $7.7\mu\text{m}$ (Smith et al. 2007). We determine color corrections to the measured fluxes from model SEDs (Section 3.1). We compute preliminary model SEDs for each cluster member from the photometry with all other corrections applied. We then integrate the model SED across the various MIR bandpasses and determine the appropriate color corrections following the procedures outlined in the instrument handbooks. The color correction, K , applied to an IRAC source is given by,

$$K = \frac{\int (F_\nu / F_{\nu_0}) (\nu / \nu_0)^{-1} R_\nu d\nu}{\int (\nu / \nu_0)^{-2} R_\nu d\nu} \quad (2)$$

where F_ν is the model spectrum and R_ν is the response function of the detector in the appropriate channel. The formalism for MIPS color corrections is similar but slightly more complicated; we refer interested readers to Section 3.7.4 of the MIPS Instrument Handbook.

⁸ http://ssc.spitzer.caltech.edu/mips/mipsinstrumenthandbook/MIPS_Instrument_Handbook.pdf

⁹ <http://ssc.spitzer.caltech.edu/dataanalysis/tools/tools/contributed/general/stinytim/>

Optical and MIR photometry for each cluster member after all relevant corrections have been applied are listed in Table 2.

3. METHODS

We wish to identify cluster members hosting AGNs, determine the AGN luminosities, examine the properties of AGN host galaxies, and determine whether they differ in any appreciable way from “normal” cluster galaxies or from their counterparts in the field. This requires that we distinguish cluster members from foreground and background galaxies, fit model SEDs to the member photometry, and measure the rest-frame properties of the AGN host galaxies. We describe the model SEDs in Section 3.1. Using these models, we calculate K-corrections to the measured fluxes, estimate stellar masses and SFRs for cluster member galaxies, and identify AGNs.

We use redshifts reported in Martini et al. (2007) or extracted from the NASA Extragalactic Database¹⁰ to identify members of the galaxy clusters in our sample. We define a galaxy to be a cluster member if it falls within a circular field with radius,

$$R < R_{200} = 1.7h^{-1} \text{ Mpc} \left[\frac{\sigma}{1000 \text{ km s}^{-1}} \right] [(1+z)^3 \Omega_m + \Omega_\Lambda]^{-1/2} \quad (3)$$

where σ is the cluster’s velocity dispersion (Treu et al. 2003). We also require that members have spectroscopic redshifts within the $\pm 3\sigma$ redshift limits prescribed in Table 1 of Martini et al. (2007), which were established using the biweight velocity dispersion estimator of Beers et al. (1990). This criterion yields a sample of 1165 cluster member galaxies. We eliminate many of these galaxies from our sample due to either limited photometric coverage or, in a few instances, because the spectroscopic redshifts in the literature are clearly in disagreement with the photometric redshifts obtained from the SED fits (Section 3.1). The final sample of “good” cluster members, those galaxies with detections in at least 5 bands and with apparently reliable spectroscopic redshifts, contains 488 galaxies.

3.1. Model SEDs

Assef et al. (2010; hereafter A10) constructed empirical SED templates that can be used to determine photometric redshifts and K-corrections for galaxies and AGNs over a wide range of redshifts. The A10 templates include three galaxy templates (elliptical, spiral, and starburst or irregular) and a single AGN template, which can be subjected to variable intrinsic reddening. These templates were derived empirically across a long wavelength baseline (0.03–30 μm), using 14448 apparently “pure” galaxies and 5347 objects showing AGN signatures. We fit two independent model SEDs to the photometry of each cluster member using the published codes of A10. The first model included only the three galaxy templates, while the second also included an AGN component. The χ^2 differences between the two fits can be used to identify AGNs (Section 3.2). Model SEDs for the M06 X-ray point sources included in our sample of “good” galaxies

are shown in Figure 1. AGNs identified from their SED fits, but which have no X-ray counterparts, are shown in Figure 2. The fits to the X-ray point sources are representative of the fit quality returned for all cluster members, while the fits to photometrically-identified AGNs are, on average, poorer.

The model SEDs fit to 25 of the 488 spectroscopically-identified cluster members are poorly matched to the measured photometry ($\chi^2 > 25$). We determine photometric redshifts for all of the identified cluster members, and in cases where the measured photometric redshifts are more than 3σ away from the cluster redshift, we replace the spectroscopic redshifts with photometric redshifts and repeat the fit. In 11 cases, this procedure results in substantial improvements to the fits ($\Delta\chi^2 > 12$, $\chi^2_{\text{photo}-z} < 4$). This suggests that some galaxies in the sample have erroneous spectroscopic redshifts. One such object is an X-ray source, identified as AC 114-5 by M06. The redshift for this object was reported by Couch et al. (2001; their galaxy #365). The spectra used by these authors covered a relatively narrow wavelength range ($8350\text{\AA} < \lambda < 8750\text{\AA}$) and had moderately poor S/N. We suspect that this combination of factors, in concert with a strong prior in favor of cluster membership in the presence of a putative H α emission line at the correct redshift, led Couch et al. (2001) to mis-identify the [OII] $\lambda\lambda 4354$ and [OIII] $\lambda\lambda 4363$ emission lines of a background quasar at $z = 0.988$ as the [NII] $\lambda\lambda 6548$ and H α emission lines, respectively, at the cluster redshift. Four of the 5 objects flagged as having erroneous redshifts in AC 114 have redshifts from Couch et al. (2001). Two of the four have redshifts from only one emission line, and we have confirmed that both objects with redshifts from multiple emission lines have plausible pairs of lines near the photometric redshifts. Furthermore, all of the objects with apparently erroneous redshifts are quite faint, having $V \lesssim 22$, which makes acquiring high-S/N spectra difficult. Our identification of objects with discrepant photometric and spectroscopic redshifts as interlopers appears to be reliable, and we eliminate the associated galaxies from further consideration. The absence of AC 114-5 from the X-ray AGN sample has important repercussions, which we discuss in Section 4.

3.2. AGN Identification

We consider AGNs selected based on their X-ray luminosities, the shapes of their SEDs, or both. X-ray sources with $L_X > 10^{42} \text{ erg s}^{-1}$ are unambiguously AGNs, but a number of processes can produce X-ray luminosities in the 10^{40} – $10^{42} \text{ erg s}^{-1}$ range. These include LMXBs, HMXBs and a galaxy’s extended, diffuse halo gas. The integrated X-ray luminosities of LMXBs and hot halo both correlate strongly with stellar mass, as measured by the galaxy’s K-band luminosity (Kim & Fabbiano 2004; Sun et al. 2007), and the luminosity from HMXBs correlates with SFR (Grimm et al. 2003). These correlations allow us to predict the X-ray luminosity of a normal galaxy using only parameters that can be measured from the model SEDs. Similar analyses were performed by Sivakoff et al. (2008) and Arnold et al. (2009), who used K-band luminosities measured from 2MASS photometry rather than luminosities estimated from model SEDs.

¹⁰ <http://nedwww.ipac.caltech.edu/>

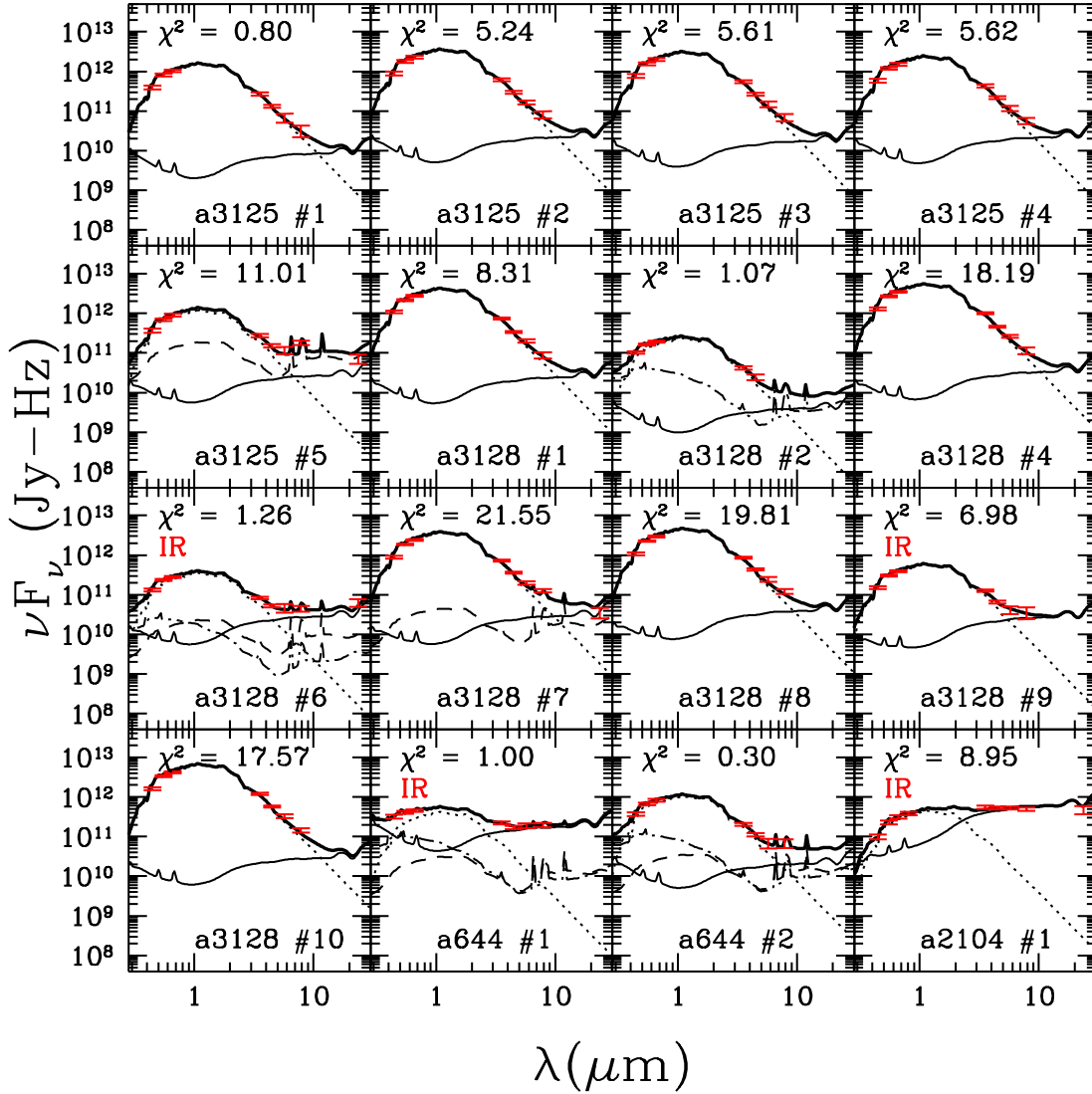


FIG. 1.— Model SEDs for galaxies hosting M06 X-ray point sources. Bands shown are, in order of wavelength, B , V , R , I , $[3.6]$, $[4.5]$, $[5.8]$, $[8.0]$ and $[24.0]$. The panels are labeled with the names assigned by M06 in their Table 4. Objects also identified as AGNs from their SED fitting are labeled “IR.” The heavy lines show the total model SED, while the *solid*, *dotted*, *dashed* and *dot-dashed* lines show the A10 AGN, elliptical, spiral and irregular templates, respectively. Not all components appear in all panels. See Section 3.1 for further details.

We measure K -band magnitudes from the model SEDs and determine SFRs from the K -corrected $8\mu\text{m}$ and $24\mu\text{m}$ luminosities of X-ray sources in each cluster. We use L_K and SFR in Eqns. 4, 5 and 6 to predict the expected X-ray luminosities from the host galaxies of X-ray point sources identified by M06 (Kim & Fabbiano 2004; Grimm et al. 2003; Sun et al. 2007, respectively). The predictions for X-ray emission from a given galaxy due to LMXBs, HMXBs and the thermal halo are good to within ~ 0.3 dex and are given by,

$$L_X(\text{LMXB}; 0.3 - 8 \text{ keV}) = [(0.20 \pm 0.08) \times 10^{30} \text{ erg s}^{-1}] \frac{L_K}{L_{K,\odot}} \quad (4)$$

$$L_X(\text{HMXB}) = 2.6 \times 10^{39} \text{ erg s}^{-1} \left[\frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} \right]^{1.7} \quad (5)$$

$$L_X(\text{thermal}; 0.5 - 2 \text{ keV}) = 2.5 \times 10^{39} \text{ erg s}^{-1} \left[\frac{L_{K_s}}{10^{11} L_\odot} \right]^{1.63 \pm 0.13} \quad (6)$$

where L_K and L_{K_s} are the galaxy’s luminosities in the K - and K_s -filters. Each relation is given in slightly different energy ranges, none of which coincide with the range used by M06. This problem is especially severe for Eqn. 5, because Grimm et al. (2003) take their X-ray fluxes from various sources in the literature without converting them to a common energy range. They claim that the resulting uncertainty is small because the scatter in the relation is much larger than the bandpass corrections. Fortunately, even if this were not the case, the HMXB contribution to the total predicted X-ray luminosities is small for the SFRs typical of cluster galaxies ($< 10 M_\odot \text{ yr}^{-1}$). The contribution from thermal emission to the soft X-ray luminosity can be significant, dominating the LMXB

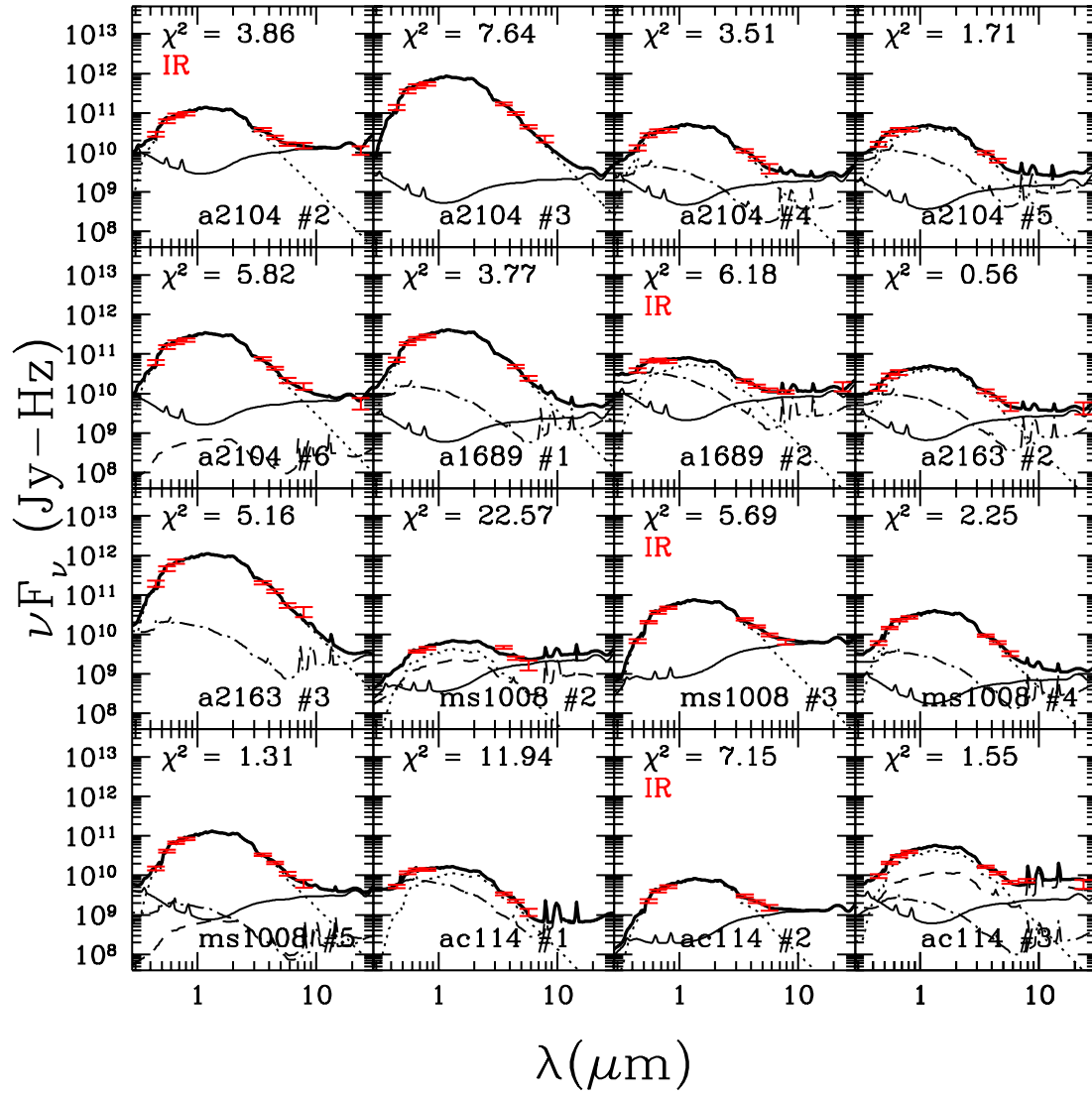


FIG. 1.— Continued

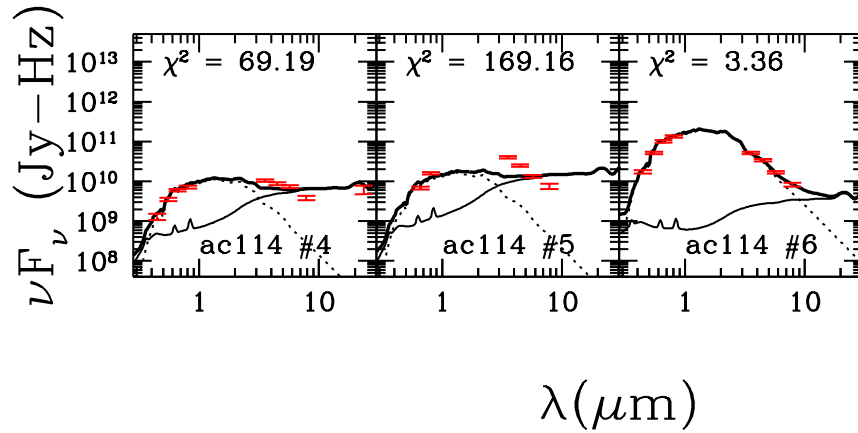


FIG. 1.— Continued. The poor fit to AC114#5 indicates a bad spectroscopic redshift.

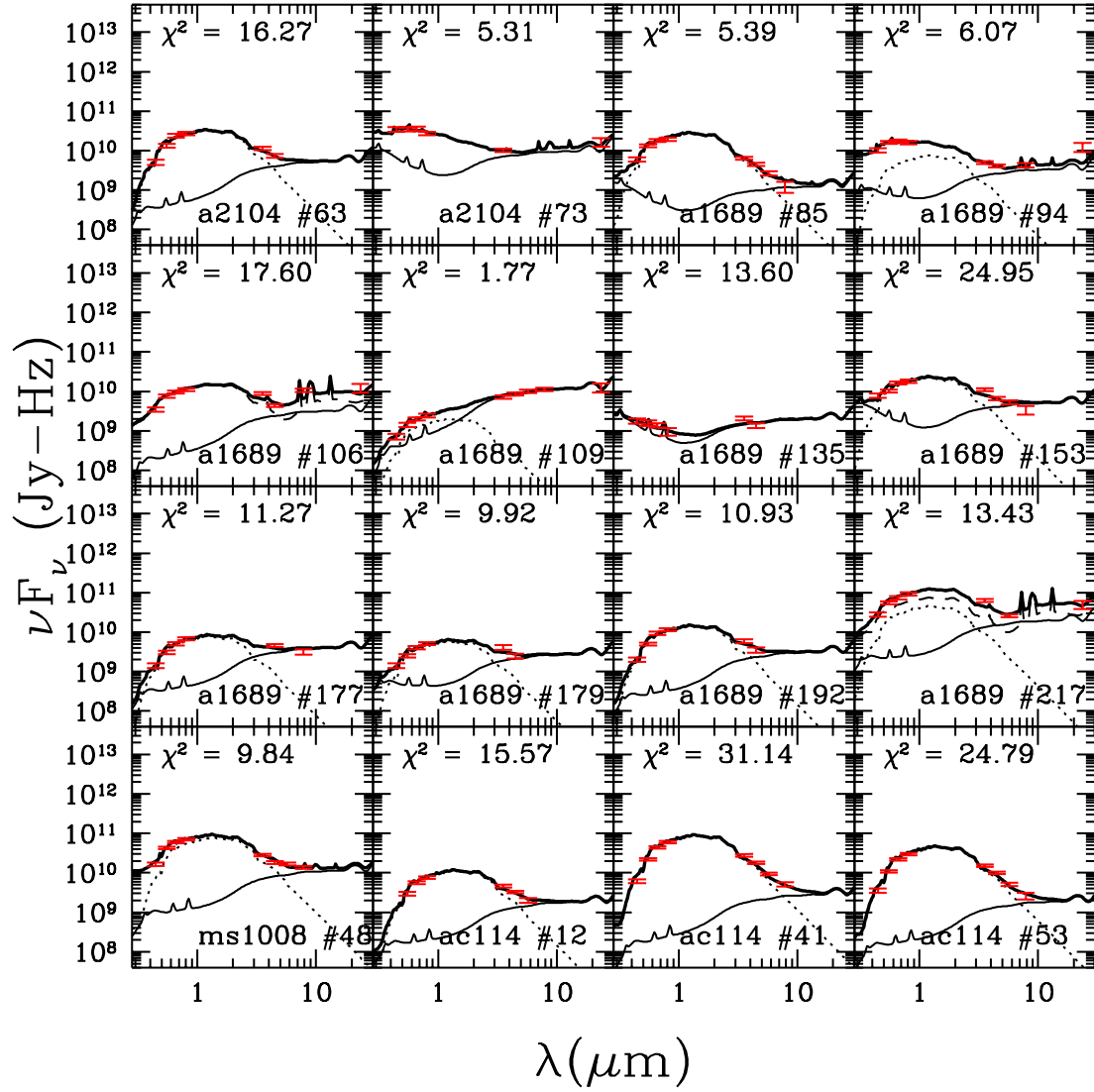


FIG. 2.— Model SEDs for objects identified as IR AGNs which are not also identified as X-ray AGNs. Line types and bandpasses shown are the same as in Figure 1. The object names indicated on each panel correspond to those in Table 1. See Section 3.1 for further details.

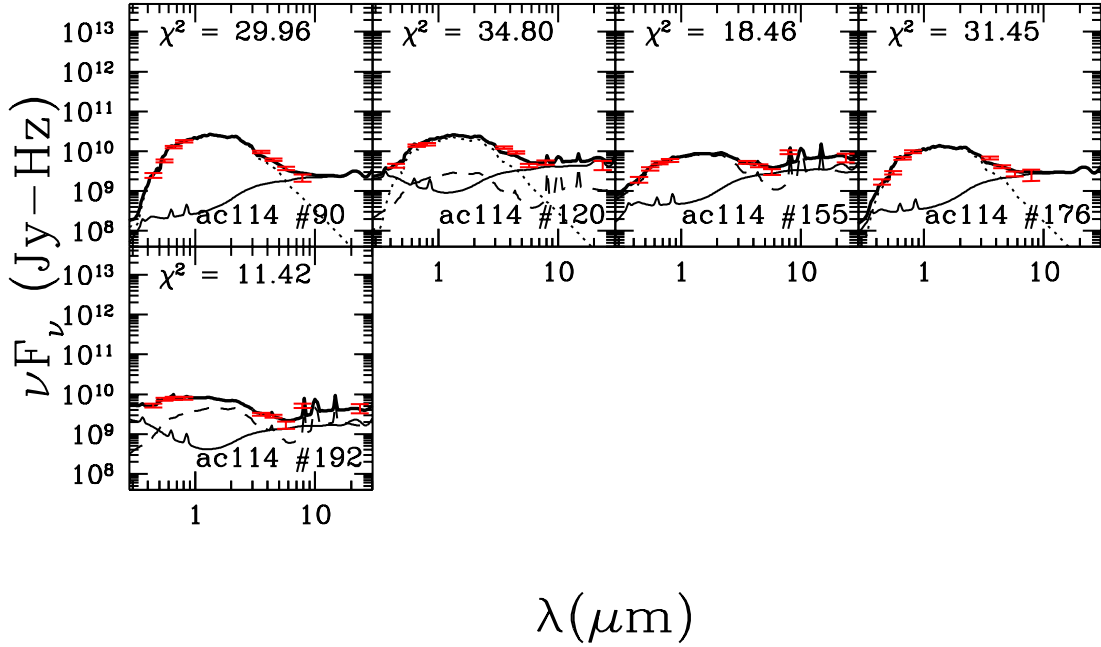


FIG. 2.— Continued

component for $L_{soft} \gtrsim 6 \times 10^{40} \text{ erg s}^{-1}$. This transition luminosity depends on the specific form adopted in Eqn. 6. Mulchaey & Jeltima (2010) found that $L_X(\text{corona}) \propto L_K^{3.9 \pm 0.4}$ for field galaxies, which differs significantly from the results of Sun et al. (2007). While the Mulchaey & Jeltima (2010) relation is not strictly applicable to our sample, the difference between cluster and field galaxies suggests that the thermal X-ray emission from a galaxy's halo depends on its environment. Such a variation introduces a systematic uncertainty in $L_X(\text{corona})$ of up to 0.8 dex at $L_K = 4 \times 10^{11} L_\odot$. Hereafter we neglect this uncertainty, as its effect in a given cluster is impossible to quantify given the data presently available.

We convert Eqns. 4-6 to determine luminosities in the soft X-ray (0.5-2 keV) and hard X-ray (2-8 keV) bands, assuming a $\Gamma = 1.7$ power law for the LMXB and HMXB relations. We further assume that the Grimm et al. (2003) relation corresponds to luminosities in the 2-10 keV range and that the thermal emission from the $kT = 0.7$ keV halo gas is negligible in the hard X-ray band. The X-ray luminosities reported by M06 and our estimates of the systematic uncertainties in these luminosities associated with the choice of energy correction factor (ECF) are shown in Figure 3, along with the predicted luminosities from the host galaxies. Many of the reported point sources require an AGN component, but several of the M06 point sources have very massive host galaxies, and their observed fluxes may arise entirely from non-AGN sources.

M06 selected 40 X-ray point sources with reliable detections above the extended emission from the surrounding ICM ($N_{count} \geq 5$). Of these 40 sources, they identify 35 as probable AGNs. We have sufficient photometry to construct reliable model SEDs for 35 M06 X-ray point sources. The remaining 5 M06 point sources either

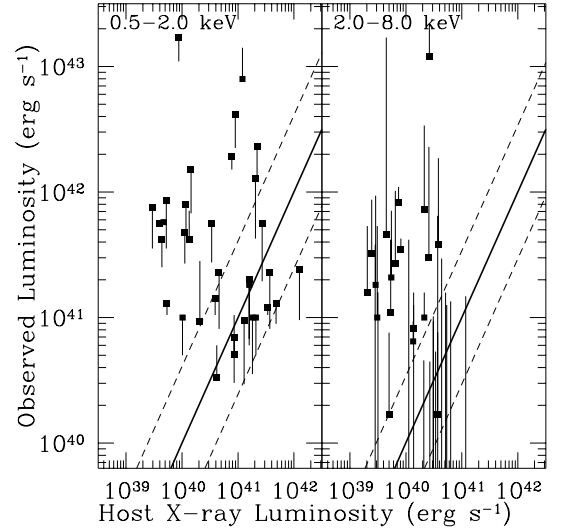


FIG. 3.— Comparison of the X-ray luminosities of X-ray point sources from M06 (y-axis) to the predicted X-ray luminosities of their host galaxies (x-axis). Points show the measured luminosities, and the “tails” connect each source to the luminosity estimated by separating its 0.5 – 8.0 keV X-ray luminosity into soft and hard components using a $\Gamma = 1.7$ power-law. The length of the tail indicates how well the measured photon energies are described by a $\Gamma = 1.7$ power law, and consequently describes the systematic uncertainty on the quoted L_X . Long tails belong to objects poorly described by a $\Gamma = 1.7$ power law. Heavy lines mark the line of equality ($L_X = L_{host}$), and the dashed lines show the ± 0.7 dex scatter about the empirical relations used to predict the X-ray luminosity of a given host galaxy. See Section 3.2 for the method used to predict X-ray luminosities of normal galaxies.

lack enough data to produce a reliable model SED or fall outside the *R*-band field of view. We find that 23 of these 35 sources have X-ray luminosities more than 1σ greater than the predicted host luminosity. Henceforth, we will call these objects X-ray AGNs. The systematic

flux error estimates in Figure 3 indicate that many X-ray AGNs have photon energy distributions that are poorly matched to the $\Gamma = 1.7$ power-law assumed by M06. Three such AGNs are close to the boundary separating probable AGNs from more ambiguous cases and have too large a soft X-ray flux compared to their hard X-ray flux to be consistent with a $\Gamma = 1.7$ power law. M06 did not correct for X-ray absorption, and in the cases where the ratio of soft to hard X-ray photons is too low for a $\Gamma = 1.7$ power law, absorption may explain the apparent discrepancy. However, objects whose soft X-ray fluxes are unexpectedly large compared to the total cannot result from absorption.

Many narrow-line Seyfert 1 galaxies (NLS1) show excess soft X-ray emission (Arnaud et al. 1985). However, only one X-ray source identified by M06 is a NLS1 (their Abell 644 #1), so the soft X-ray excess common to NLS1s cannot explain the presence of excess soft X-ray emission in 13 X-ray sources with AGN-like luminosities. Alternative explanations include soft X-rays arising from gas that is photoionized by an obscured AGN (e.g. Ghosh et al. 2007), poor signal-to-noise in the X-ray, and thermal emission from hot gas. The ECF used to convert soft X-ray photons to incident fluxes for $kT = 0.7$ keV thermal bremsstrahlung (assumed by Sun et al. 2007) is larger than the ECF for a $\Gamma = 1.7$ power law by approximately 10%. This implies that two of the three suspect X-ray AGNs have luminosities sufficiently close to the threshold that they may reasonably be mis-classified galaxies. This yields a possible contamination in the X-ray AGN sample of approximately 10%, which is comparable to the estimated contamination of the IR AGN sample (see below).

In comparison to our sample of 23 X-ray AGNs from a parent sample of 35 X-ray point sources with complete photometry, M06 found that 35 of their 40 point sources had X-ray luminosities consistent with AGNs. The larger fraction of AGNs reported by M06 may be attributed to their use of L_X – L_B relations, which show larger scatter than the K -band relations. We also introduce some uncertainty by estimating L_K from the model SEDs, but this uncertainty is small ($\sim 10\%$) compared to the scatter in the L_X – L_K relation. An additional difference is that M06 considered the two luminosity components separately and did not compare their sum to the measured luminosities. This was done subsequently by Sivakoff et al. (2008) and Arnold et al. (2009) in their studies of AGNs in low-redshift groups and clusters of galaxies. Their analyses are much closer to our method, and their samples included some of the clusters in our sample (Abell 3128, 3125 and 644).

An alternative method to identify AGNs is to use the distinctive shape of their SEDs, particularly in the MIR (e.g. Marconi et al. 2004; Stern et al. 2005; Richards et al. 2006; A10). This approach can identify AGNs behind gas column densities large enough to obscure even the X-rays emitted by an AGN. Such an AGN sample has very different selection criteria and biases than an X-ray selected sample, and combining the two results in more complete AGN identification.

We identify AGNs from their SEDs by comparing the goodness-of-fit of two sets of model templates. The first set uses only the normal galaxy templates. The other also includes the AGN template. We determine whether

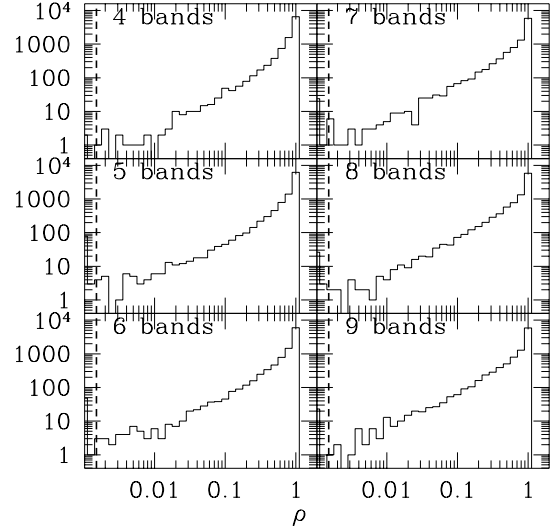


FIG. 4.— Likelihood ratio (ρ) distributions for fits to model galaxies with no AGN component after photometric errors have been added. Each panel shows the distributions resulting from examining 10,000 normal galaxies. Galaxies with $\rho = 1$ are well-fit by the three normal galaxy templates and do not require an AGN component. An object with $\rho = 0$ would be perfectly fit by the 4-template model SED and have $\chi^2_{gal+AGN} = 0$. The dashed line indicates the selection threshold, ρ_{max} used to identify IR AGNs. See Section 3.2 for further details.

a given galaxy requires an AGN component in its model SED by applying a threshold on the likelihood ratio, ρ ,

$$\rho = \frac{\exp[-\chi^2(gal)/2]}{\exp[-\chi^2(gal + AGN)/2]} \quad (7)$$

where $\chi^2(gal)$ and $\chi^2(gal + AGN)$ are goodnesses-of-fit for a model with only the A10 galaxy templates and for a model that includes an additional AGN component, respectively. AGNs are those objects whose ρ is smaller than a pre-determined selection limit, ρ_{max} , established by Monte Carlo simulations of normal galaxies.

We created artificial galaxy photometry to determine an appropriate ρ_{max} by combining the three galaxy templates of A10 in proportions that reflect the template luminosity distributions in real cluster members. We introduced Gaussian photometric errors comparable to the photometric uncertainties in our real data (0.07 mag) to the fluxes given by the model SEDs. We also allowed occasional catastrophic errors of up to 0.3 dex. The artificial galaxy photometry did not include upper limits, which we also neglected when constructing model SEDs of real galaxies. We fit the artificial galaxies with two models. The first model excluded the AGN component from the fit, while the second component included it. The likelihood ratio distributions computed from the goodness-of-fit results for the two different models are shown in Figure 4. These distributions show the probability that a pure galaxy will be erroneously classified as an AGN due to the presence of photometric errors. The similarity of the different distributions, even based on only 4 photometric bands, indicates that a single ρ_{max} can be used to select AGNs from among all galaxies in our sample.

We also identify AGNs based on the F-statistics of the two model SED fits described above. Figure 5 shows

the F-statistic as a function of $\chi^2(gal)$ for X-ray AGNs selected using Figure 3, AGNs selected using likelihood ratios, and “normal” cluster members. The F-statistic is given by,

$$F = \frac{\Delta\chi^2/2}{\chi^2_{\nu}(gal + AGN)} \quad (8)$$

where $\Delta\chi^2$ is the (absolute) change in the total χ^2 after introducing the AGN component to the fit. In addition to the galaxies that are well-fit by the galaxy-only model and not substantially improved by the addition of an AGN component, there are objects with large $\chi^2(gal)$ but small F , and objects with large F but small $\chi^2(gal)$. Neither of the latter two categories contain objects likely to be AGNs from the point-of-view of the model SEDs. The most luminous X-ray AGNs have both large F and large $\chi^2(gal)$. These are clearly identified as AGNs by the model SEDs, and less luminous X-ray AGNs can be found with increasing density toward the normal galaxy locus at the origin of Figure 5. The dotted and dashed lines in the Figure correspond to the $\rho < \rho_{max}$ selection boundaries for $N=6$ and $N=9$ flux measurements, respectively. Some objects above the $N=9$ line are not selected as IR AGNs because they fail a cut on the overall goodness-of-fit, which requires $\chi^2_{\nu}(gal + AGN) < 5$. We could define an AGN selection region in Figure 5, but due to the non-uniformity of our photometric data, this would result in different effective cuts in $\Delta\chi^2$ between different clusters and between objects in individual clusters. Furthermore, we find that only 3 AGNs identified using likelihood ratios fall into the suspect part of Figure 4 with $F \approx 1$. This level of contamination ($\sim 10\%$) is consistent with the estimated purity of the X-ray AGNs, which we deem to be acceptable. Therefore, for the rest of this work, we rely on the more simplistic likelihood ratio threshold to identify AGNs.

Likelihood ratio selection of AGNs using SED fitting is most sensitive to the shape of the MIR SED, so we refer to AGNs so identified as IR AGNs. We find 29 IR AGNs using a selection boundary at the 99.8% confidence interval of the merged ρ distribution ($\rho_{max} = 1.5 \times 10^{-3}$). Table 1 lists both X-ray and IR AGNs, their luminosities, and the basic parameters of their host galaxies. IR AGN selection recovers 5 of 7 AGNs (71%) identified via the Stern wedge (Stern et al. 2005, see Figure 6) and 8 of the 23 X-ray AGNs. The galaxies in the Stern wedge that are not selected from their SED fits fall just inside the boundary of the wedge, so they may be normal galaxies shifted into the wedge by photometric errors. Gorjian et al. (2008) find that 35% of X-ray sources in the Boötes field of the NOAO Deep Wide Field Survey ($f_X > 8 \times 10^{-15}$ erg s $^{-1}$ cm $^{-2}$) with detections in all 4 IRAC bands fall outside the Stern wedge, and Figure 14 of A10 shows that a substantial fraction of the point-source (luminous) AGNs in their sample fall outside the wedge as well. Given the high luminosities in both of these samples, it is perhaps not surprising that most of the lower-luminosity AGNs common in galaxy clusters fall outside the Stern wedge. For $\rho_{max} = 1.5 \times 10^{-3}$ and the size of our sample (488 galaxies), we expect on average one false-positive AGN identification and 3 or fewer false-positives at 98% confidence, implying $> 90\%$ purity in our IR AGN sample.

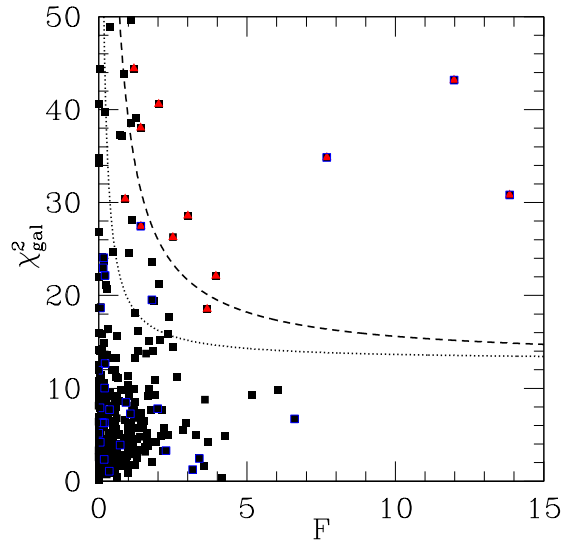


FIG. 5.— Application of F-statistics for AGN identification based on fits of galaxy-only and galaxy-plus-AGN model SEDs to measured photometry. Red triangles show AGNs identified using the ρ threshold shown in Figure 4 (IR AGNs). Open blue squares show X-ray AGNs, and solid black squares show “normal” cluster members. The dotted and dashed curves show the ρ thresholds for objects having $N=6$ and $N=9$ flux measurements, respectively. Objects above their corresponding selection boundaries are identified as AGNs, provided that they pass a χ^2_{ν} cut.

We estimate the completeness of the IR AGN sample as a function of the reddening of the AGN template and luminosity using Monte Carlo simulations. We construct model AGN SEDs by injecting an AGN component with some luminosity and reddening into artificial galaxy photometry, which we generate using the Monte Carlo techniques described above. We estimate the completeness of the IR AGN sample from the fraction of such AGNs recovered. The completeness depends strongly on the luminosity of the AGN component. We only reliably identify AGNs with $L_{bol} \gtrsim 7 \times 10^{10} L_{\odot}$. The completeness depends only weakly on $E(B - V)$. There are measurable differences only for AGNs with $E(B - V) > 2$. For our observed wavelengths, AGN identification depends most strongly on the shape of the MIR SED, which is insensitive to modest amounts of reddening. The full dependence of completeness on L_{bol} and $E(B - V)$ is listed in Table 2.

We caution that both our AGN identification and the analysis below were conducted using the fixed AGN template derived by A10. While this template is dominated by luminous AGNs, AGNs of all luminosities were used in its construction, and in some sense it represents the optimal median AGN SED. There is some evidence that AGNs with low Eddington ratios (L_{bol}/L_{Edd}) are systematically weaker in the UV and the MIR than higher L_{bol}/L_{Edd} AGNs. This appears to become important at $L_{bol}/L_{Edd} \approx 10^{-3}$ (Ho 2008). However, the UV weakness of such objects remains a subject of debate (e.g. Ho 1999, 2008; Dudik et al. 2009; Eracleous et al. 2010), and the SEDs of AGNs appear to all be quite similar out to $\lambda \approx 20 \mu m$, even in AGNs with accretion rates as low as $L_{bol}/L_{Edd} \approx 10^{-3}$ (Ho 2008, Figure 7). Furthermore, the variable reddening of the AGN component allowed by the models can account for differing UV/visible flux ratios, making the AGN component of the model SEDs

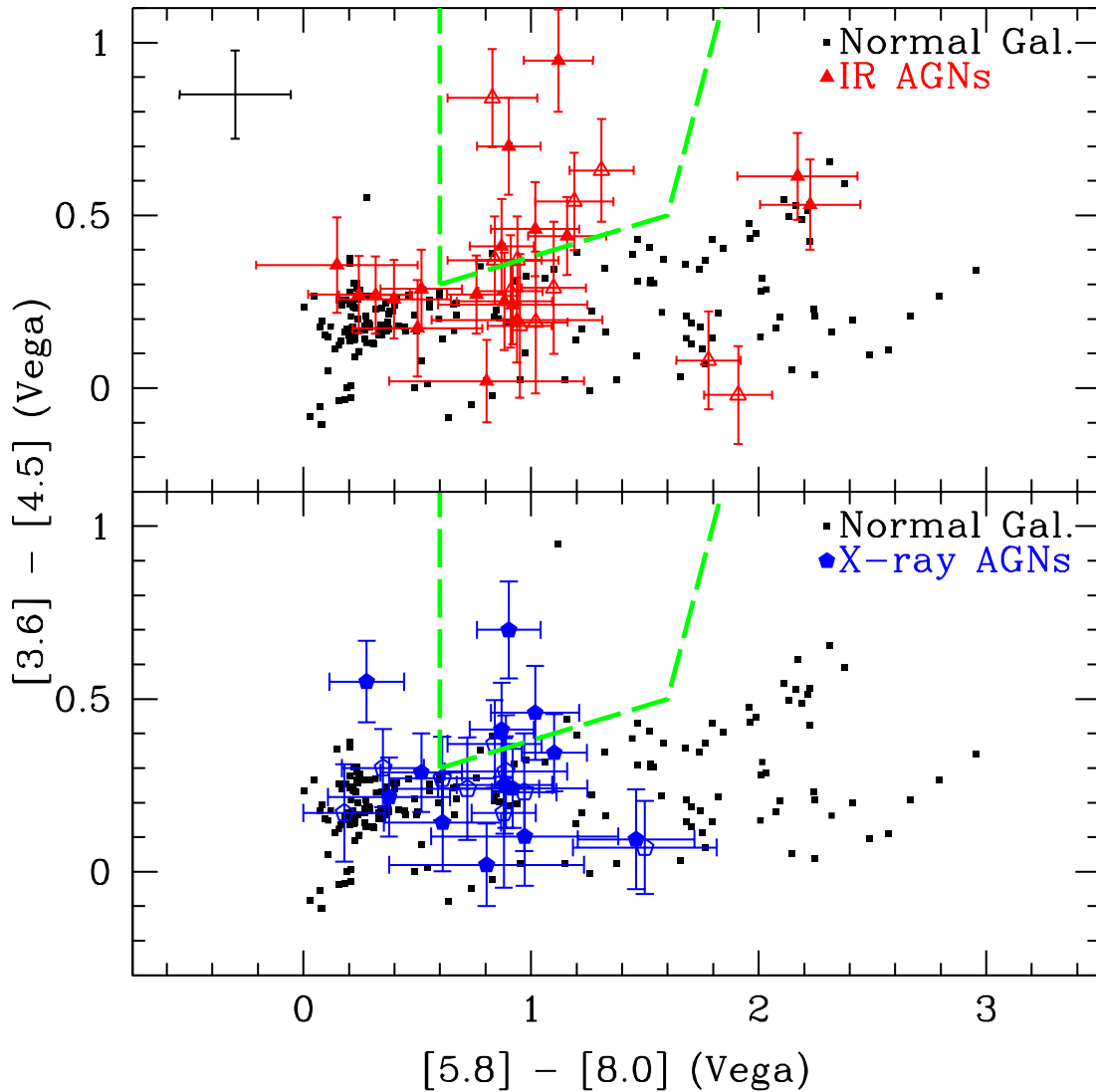


FIG. 6.— Positions of both IR AGNs (red triangles, upper panel) and X-ray AGNs (blue pentagons, lower panel) on the Stern et al. (2005) AGN selection diagram. The dashed, green trapezoid marks the Stern wedge. Filled symbols mark AGNs whose colors were determined using only measured magnitudes; open symbols show colors determined using model SEDs to estimate magnitudes in missing IRAC bands. No model colors were constructed for normal galaxies. Passive galaxies are located in the lower-left corner, normal star-forming galaxies are found in the center, and (U)LIRGs occupy the upper-right part of the galaxy sequence. The error bars in the upper-left show the color uncertainty for a typical cluster member, including AGNs.

flexible enough to mimic AGNs with a wide variety of Eddington ratios.

Intrinsic variations in the AGN SED are one possible cause of the absence of an important AGN component in the SEDs of many X-ray AGNs, despite their similar distributions in L_{bol} (Section 4). Another possible explanation is that the nuclear MIR emission from many X-ray AGNs is overwhelmed by star-formation in their host galaxies. We find that X-ray AGNs with $L_X > 10^{42} \text{ erg s}^{-1}$ that are also identified as IR AGNs have no measurable star-formation, while those not identified in the IR have $\langle \text{SFR} \rangle = 0.3 M_\odot \text{ yr}^{-1}$. This may be a selection effect, since nuclear MIR emission is not subtracted before computing SFRs in galaxies not identified as IR AGNs. However, it appears that the balance between SFR and nuclear emission is an important factor in determining whether a given X-ray source will be

identified as an IR AGN.

Also of concern is the MIR emission exhibited by some normal galaxies which is clearly not associated with star-formation (e.g. Verley et al. 2009; Kelson & Holden 2010). The strength of the diffuse interstellar dust emission relative to star formation varies from galaxy to galaxy depending on the populations of AGB stars, which can produce and heat dust (Kelson & Holden 2010), and field B-stars (including HB stars), which produce UV light that can both heat dust grains and excite PAH emission in the diffuse ISM (e.g. Li & Draine 2002). These effects could mimic the presence of an AGN, particularly in passively-evolving galaxies, which the A10 templates predict should decline strictly as a $\nu F_\nu \propto \nu^{2.5}$ power-law. Given the limited data available to constrain MIR emission not associated with either an AGN or a star-forming region and the as-yet uncertain magnitude

of the associated variations, we neglect any potential effects on our AGN identification. However, potential sources of MIR emission not accounted for by the A10 templates, especially emission from dust heated by old stars in passive galaxies, remain a potentially important systematic uncertainty.

3.3. Stellar Masses

Stellar population synthesis modeling provides a means to estimate stellar masses in the absence of detailed spectra. Bell & de Jong (2001) construct model spectra of galaxies for a wide variety of stellar masses, SFRs, metallicities and stellar initial mass functions (IMFs) to convert colors to mass-to-light ratios (M/L). Their models assume a mass-dependent formation epoch with bursty star-formation histories, which is appropriate for the spiral galaxies they study. Figure 9 of Bell & de Jong (2001) makes it clear, however, that their results also robustly estimate M/L for passively evolving galaxies. In fact, the scatter about the mean M/L tends to decrease for redder systems because the stochasticity of the star-formation history becomes less important in galaxies that experienced their last burst of star-formation in the distant past.

Bell & de Jong provide a table of coefficients (a_λ, b_λ) relating M/L for a galaxy to its color,

$$\log_{10}(M/L_\lambda) = a_\lambda + b_\lambda \times \text{color} \quad (9)$$

where *color* is measured in the bands for which a_λ and b_λ were determined. We adopt the coefficients appropriate for Solar metallicity computed with the Bruzual & Charlot (2003) population synthesis code and the scaled Salpeter IMF suggested by Bell & de Jong (2001), who report that a modified Salpeter IMF with total mass $M' = 0.7M_{\text{Salpeter}}$ yields the best agreement with the Tully-Fisher relation. Once we select an appropriate (a_λ, b_λ) pair, it is straightforward to compute stellar masses from the visible photometry. However, we must first subtract the AGN component of the model SED in sources identified as IR AGNs before computing colors.

The uncertainty introduced by the AGN subtraction is a combination of the fractional uncertainty in the contribution of the AGN template to the model SED, which is determined by the fit, and the uncertainty in the AGN template itself. To measure the uncertainty in the template, we examined 1644 luminous quasars with spectroscopic redshifts from the AGN and Galaxy Evolution Survey (AGES; Kochanek et al. in prep) and determined the variation in their measured photometry about their best-fit model SEDs. Using these measurements, we constructed an RMS SED for AGNs and averaged it across each of the bandpasses we employ. The uncertainty in the AGN correction resulting from intrinsic variation about the AGN template is 10% except at $24\mu\text{m}$, where there are too few $z = 0$ quasars to make a meaningful comparison. The uncertainty in the AGN correction at $24\mu\text{m}$ is therefore large, but it can be constrained by the relatively good agreement of the $8\mu\text{m}$ and $24\mu\text{m}$ SFRs (Figure 7).

In galaxies with no genuine nuclear activity the AGN template can correct for variations in stellar populations relative to the templates, intrinsic extinction, or errors in the measured photometry. Subtraction of the AGN com-

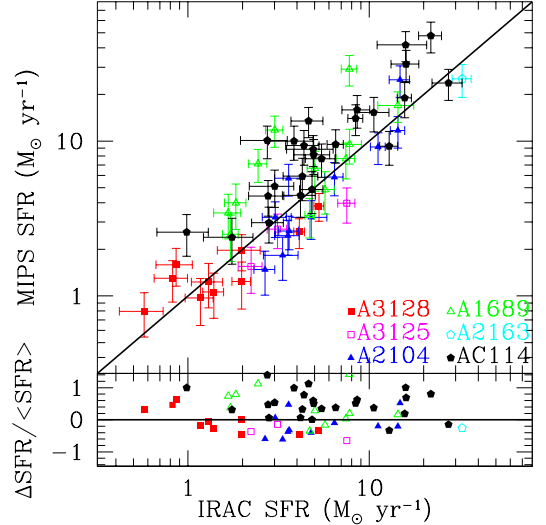


FIG. 7.— Comparison of SFRs determined using the IRAC and MIPS relations of Zhu et al. (2008). The solid lines in both panels denote equality. The bottom panel shows the fractional residuals between the two star-formation indicators. The MIPS SFRs are biased high with respect to IRAC SFRs by 0.1 dex, which is significant at 2.4σ but smaller than the intrinsic scatter (0.2 dex).

ponent under these circumstances would result in underestimated stellar masses and SFRs, while failure to subtract the AGN component in a genuine, low-luminosity AGN would cause the measured SFRs of their host galaxies to be biased toward higher values. However, the ambiguity between a genuine, low-luminosity AGN and an apparent AGN component introduced to correct for photometric errors (Section 3.2) renders any attempt to subtract the AGN component in such cases suspect. Therefore, in normal galaxies and in X-ray AGNs not identified as IR AGNs, no AGN correction is applied. We accept the inherent bias to avoid introducing ambiguous AGN corrections, which would be much more difficult to interpret.

The Bell & de Jong (2001) calibrations are reported for rest-frame colors, so we need K-corrections for each cluster member to convert the measured magnitudes to the rest frame. We calculate the K-corrections from the model SEDs returned by the A10 fitting routines. Uncertainties on K-corrections cannot be directly determined from the uncertainties in the model components because K-corrections depend non-linearly on these uncertainties. Therefore, we recombine the components of each model SED in proportion to the uncertainties in their contributions to the total model flux. This results in a series of temporary model SEDs. We then calculate the K-corrections implied by these temporary model SEDs and measure their dispersions to estimate the uncertainties in the K-corrections returned by the original model SED.

The systematic uncertainty on the stellar masses calculated from Eqn. 9 can be estimated by comparing the fiducial masses with masses derived using different assumptions. We estimate the typical systematic uncertainty in stellar mass, listed in Table 1, to be 0.2 dex. These uncertainties are derived by measuring the difference between the fiducial masses and those determined using coefficients appropriate for the PÉGASE population synthesis models with a Salpeter IMF. Conroy et al.

(2009) studied the ability of different models to reproduce the observed colors of stellar populations in globular clusters and found that systematic uncertainties on stellar masses derived from population synthesis codes typically reach or exceed 0.3 dex.

3.4. Star-Formation Rates

We measure SFRs from our AGN-corrected MIR photometry using the empirical relations of Zhu et al. (2008), which have been determined for both the IRAC $8\mu\text{m}$ and the MIPS $24\mu\text{m}$ bands using the same calibration sample. While the contribution of the stellar continuum to the observed $24\mu\text{m}$ luminosity is negligible, the Rayleigh-Jeans tail of the stellar continuum emission can make an important contribution to the integrated flux at $8\mu\text{m}$, especially in galaxies with the low SFRs typical in clusters. The method used to subtract this contribution is an important systematic uncertainty in the SFR calculation. Zhu et al. (2008) assume that the contribution of the stellar continuum at $8\mu\text{m}$ can be described by $L_{\nu}^{\text{stellar}}(8\mu\text{m}) = 0.232L_{\nu}(3.5\mu\text{m})$, as derived from the models of Helou et al. (2004). Under this assumption, Zhu et al. (2008) derive luminosity–SFR relations appropriate for a Salpeter IMF,

$$\text{SFR}(M_{\odot} \text{ yr}^{-1}) = \frac{\nu L_{\nu}^{\text{dust}}(8\mu\text{m})}{1.58 \times 10^9 L_{\odot}} \quad (10)$$

$$\text{SFR}(M_{\odot} \text{ yr}^{-1}) = \frac{\nu L_{\nu}(24\mu\text{m})}{7.15 \times 10^8 L_{\odot}} \quad (11)$$

where $L_{\nu}^{\text{dust}}(8\mu\text{m})$ is determined by subtracting $L_{\nu}^{\text{stellar}}(8\mu\text{m})$ from the measured $8\mu\text{m}$ luminosity. Simões-Lopes et al. (*in preparation*) find that $L_{\nu}^{\text{stellar}}(8\mu\text{m}) = 0.269L_{\nu}(3.5\mu\text{m})$ provides a better estimate for their sample of nearby, early-type galaxies with no dust and conclude that the difference in their result compared to Helou et al. (2004) is due to metallicity. Another important systematic uncertainty in SFRs derived from PAHs is the dependence of the PAH abundance on metallicity (Calzetti et al. 2007) because lower metallicity systems have fewer PAHs and therefore weaker $8\mu\text{m}$ emission at fixed SFR. This second effect is negligible for the high-mass—and therefore metal-rich—galaxies we consider. We neglect both metallicity- and mass-dependent effects for the remainder of our analysis. Instead, we follow Zhu et al. (2008) and assume that $L_{\nu}^{\text{stellar}}(8\mu\text{m}) = 0.232L_{\nu}(3.5\mu\text{m})$. We derive SFRs from Eqns. 10 and 11. For galaxies having measurable ($> 3\sigma$) SFRs from both IRAC and MIPS, we take a geometric mean of the two; otherwise, we use whichever SFR measurement is available. The resulting SFRs for AGNs are summarized in Table 1.

Equations 10 and 11 were derived using the extinction-corrected $\text{H}\alpha$ luminosity of the associated galaxies. The MIPS SFR determined from Eqn. 11 for a galaxy with $\nu L_{\nu} = 7.15 \times 10^9 L_{\odot}$ is ≈ 0.6 dex larger than the SFR derived from the Calzetti et al. (2007) relation, which was calibrated using the $\text{Pa}\alpha$ emission line. Calzetti et al. (2007) used the Starburst99 IMF, and after accounting for this difference, the resulting discrepancy is reduced to 0.4 dex. The choice of SFR calibration therefore represents an important systematic uncertainty in the measured SFRs. The total systematic uncertainty in SFR

is indicated by the significant scatter (0.2 dex) and the small but marginally significant offset (0.1 dex) between the IRAC and MIPS SFRs in Figure 7. Since the offset is smaller than both the scatter about the line of equality and the systematic uncertainty when comparing to the Calzetti et al. (2007) result, we neglect it below. However, we caution that there remains a $\sim 15\%$ uncertainty in our results associated with the discrepancy between the IRAC and MIPS SFR indicators.

4. RESULTS

We identify 29 IR AGNs with likelihood ratios $\rho < \rho_{\text{max}}$. We also confirm the presence of AGNs in 23 X-ray point sources whose X-ray luminosities significantly exceed the luminosities expected from their host galaxies. Surprisingly, the X-ray and IR AGN samples are largely disjoint: only 8 AGNs appear in both. Only the more luminous IR AGNs appear in the X-ray AGN sample and vice-versa. While it is not surprising for faint X-ray AGNs to drop out of the IR AGN sample, the absence of X-ray emission associated with many IR AGNs, which require a moderately luminous AGN for a reliable detection, is unexpected. This may indicate either different selection biases in the two methods or genuine, physical differences between the AGNs selected by these techniques.

4.1. Bolometric AGN Luminosities

In order to conduct a meaningful comparison of X-ray and IR AGNs, we need to place them on a common luminosity system. The most obvious choice is the bolometric AGN luminosity (L_{bol}), which also allows us to examine black hole growth rates.

The A10 AGN template provides a natural means of determining the bolometric luminosity (L_{bol}) for IR AGNs, but the MIR luminosity in the template comes from reprocessed dust emission, which would result in double-counting the UV emission from the disk for AGNs viewed face-on (Marconi et al. 2004, hereafter M04; Richards et al. 2006). We instead determine L_{bol} using a piecewise combination of the AGN model SED and three power-laws. We integrate the unreddened A10 AGN template from $\text{Ly}\alpha$ to $1\mu\text{m}$, shortward of which the template becomes uncertain due to absorption by the $\text{Ly}\alpha$ forest. We estimate the X-ray luminosity by integrating a $\Gamma = 1.7$ power law from 1–10 keV. We estimate the extreme ultraviolet (EUV) luminosity by integrating $L_{\nu} \propto \nu^{-\alpha_{\text{ox}}}$ from $\lambda = 1216\text{\AA}$ to 1 keV. The slope of the EUV SED (α_{ox}) is given by Eqn. 2 of Vignali et al. (2003),

$$\alpha_{\text{ox}} = 0.1 \log \left[\frac{L_{\nu}(2500\text{\AA})}{\text{erg s}^{-1}} \right] - 1.32 \quad (12)$$

with $L_{\nu}(2500\text{\AA})$ taken from the AGN template SED. Finally, we eliminate reprocessed emission from dust by assuming $F_{\nu} \propto \nu^{-2}$ for $1\mu\text{m} < \lambda < 30\mu\text{m}$, following M04.

To correct the X-ray luminosities of X-ray AGNs to bolometric luminosities, we fit a power-law to the measured $L_{\text{X}}(0.3 - 8 \text{ keV})$ and L_{bol} of the 8 IR AGNs identified separately in X-rays. A least-squares fit to the total

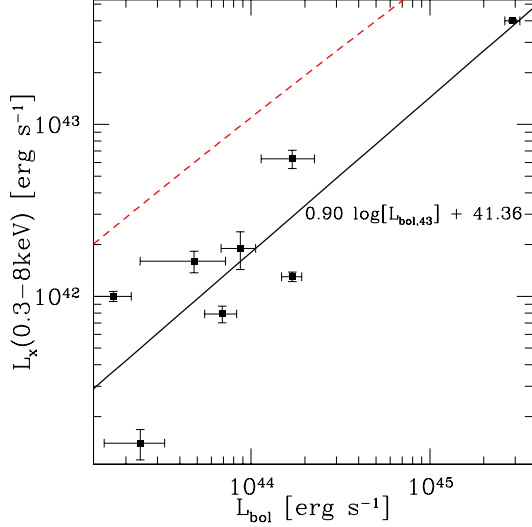


FIG. 8.— Comparison of our estimated relation between L_{bol} and L_X (black solid line) with that found by M04 (red dashed line). The measured X-ray (0.3–8 keV) and bolometric luminosities of AGNs identified by both the X-ray and IR selection criteria are shown by black points. L_{bol} is derived by integrating the A10 AGN model SED component from 1216Å to $1\mu m$ and assuming a declining continuum with $F_\nu \propto \nu^{-2}$ for $\lambda > 1\mu m$. L_X is determined assuming a $\Gamma = 1.7$ power law. See Section 4.2 for further information.

X-ray and AGN luminosities yields,

$$\log[L_X(0.3 - 8 \text{ keV})] = (0.9 \pm 0.2) \log \left[\frac{L_{bol}}{10^{43} \text{ erg s}^{-1}} \right] + (41.4 \pm 0.2) \quad (13)$$

where L_{bol} is the bolometric AGN luminosity integrated from 10 keV to $30\mu m$. The AGNs used to determine Eqn. 13 show a scatter of 0.4 dex about the best-fit relation (Figure 8). Figure 8 suggests that the slope returned by the fit may be strongly influenced by the highest-luminosity AGN. However, a fit to the other 7 AGNs returns an identical slope (0.9 ± 0.5), so Eqn. 13 is not significantly biased by the highest-luminosity object. The luminosity dependence of the bolometric corrections (BCs) derived from the fit is therefore robust. The slope is also consistent, within large statistical uncertainties, with the luminosity-dependence derived by M04.

The BCs derived from Eqn. 13 are fairly crude. For example, the fit does not account for uncertainties on L_X or L_{bol} . It also ignores upper limits, which will lead it to over-predict the true L_X at fixed L_{bol} . M04, by contrast, provide luminosity-dependent BCs in several energy ranges that account for X-ray non-detections (their Eqn. 21). We convert their BCs to 0.3–8 keV assuming $\Gamma = 1.7$ and estimate the expected X-ray flux from our IR AGNs. The predicted X-ray fluxes exceed those estimated using Eqn. 13, which we know over-estimates the intrinsic L_X – L_{bol} relation, by 0.7 dex or more. This might result if the M04 SED is a poor match to the A10 AGN template. M04 determine their X-ray BCs using the α_{ox} relation derived by Vignali et al. (2003) for a sample of SDSS quasars, including broad-absorption line quasars (BALQSOs). Given that our L_{bol} calculation is insensitive to the absorption in BALQSOs, it is possible that the M04 BCs over-estimate L_X at fixed $L_\nu(2500\text{Å})$ when applied to our sample. In order to produce consis-

tent results for the X-ray and IR AGNs, we therefore use the BCs implied by Eqn. 13 rather than the M04 BCs, despite the large uncertainties associated with Eqn. 13.

4.2. X-ray Sensitivity

With the L_X – L_{bol} relation provided by Eqn. 13, we can determine whether the X-ray non-detection of many IR AGNs results from some intrinsic difference between the two classes of AGNs or if it is merely a result of the sensitivity of the X-ray images used by M06. Eqn. 13 predicts that 9 (5) IR AGNs with no X-ray detections should be more than a factor of 3 (5) brighter than the faintest point source in their parent clusters (M06). The M04 BCs produce more X-ray flux at fixed bolometric luminosity than Eqn. 13 and yield 13 (12) IR AGNs with significant X-ray non-detections with the same flux limits. The lack of detectable X-rays from many IR AGNs is consequently easier to explain if we use Eqn. 13 rather than the M04 relations to predict their X-ray luminosities.

The minimum detected flux in a given cluster may not always be a fair representation of the sensitivity for a given IR AGN due to variations in the *Chandra* effective area with off-axis angle. However, the magnitudes by which many IR AGNs in AC 114 exceed the minimum detected flux, sometimes more than a factor of 5, suggest that these AGNs should have been detected if they obeyed the L_X – L_{bol} relation of Eqn. 13. The non-detection of many IR AGNs in X-rays is qualitatively consistent with the results of Hickox et al. (2009), whose IR AGN selection relied upon the Stern wedge, and who found many strong IR AGNs that could not be identified in X-rays. At least some of the “missing” IR AGNs could be highly obscured. An intervening absorber with $N_H = 10^{22} \text{ cm}^{-2}$ would reduce the observed 0.5–2 keV flux by a factor 3, which is sufficient to explain many of the missing IR AGNs. The missing AGNs could also result from the large scatter about the mean $L_\nu(2500\text{Å})$ – α_{ox} relation. The AGN with the most significant X-ray non-detection exceeds the minimum reported flux by a factor of 7, which can be explained by $\Delta\alpha_{ox} \approx 0.4$. Vignali et al. (2003) report a large intrinsic scatter about their best-fit relation, and the combination of this scatter with *in situ* absorption could mask moderately luminous AGNs from detection in X-rays.

Finally, at least one IR AGN (A1689 #109) appears to be absent from the M06 sample due to X-ray variability rather than as a result of absorption, intrinsic X-ray faintness, or shallow *Chandra* imaging. This object is moderately luminous ($L_{bol} = 2.1 \times 10^{40} L_\odot$), AGN-dominated ($f_{AGN} = 0.95$), falls firmly in the middle of the Stern wedge, and is very robustly detected by our likelihood ratio selection ($\rho = 4 \times 10^{-77}$). Nevertheless, there is no X-ray point source associated with this object in the *Chandra* image employed by M06. In a more recent observation (*Chandra* Obs ID 6930, PI G. Garmire), A1689 #109 is associated with an X-ray point source far brighter than the X-ray sources reported by M06. It therefore seems likely that the IR AGNs that require the most extreme values of α_{ox} could be accounted for by variability rather than by systematically weak X-ray emission compared to their visible-wavelength luminosities.

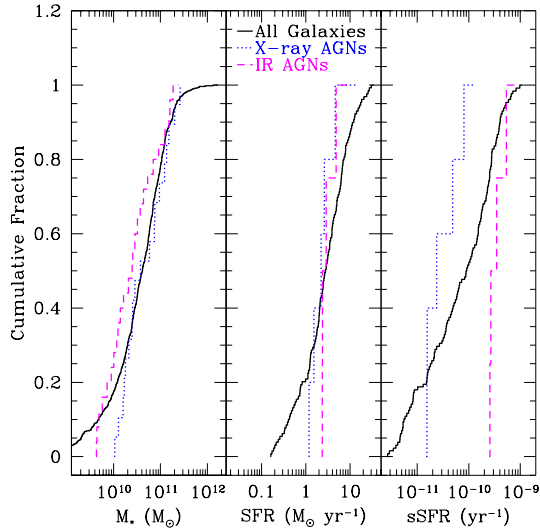


FIG. 9.— Cumulative stellar mass, SFR and sSFR distributions of the X-ray and IR AGN samples compared to the distributions for all cluster members. Neither of the AGN samples show any significant differences in either M_* or SFR compared to the full sample of cluster members, nor does the merged AGN sample. However, IR AGN hosts have higher sSFR than both X-ray AGN hosts and normal galaxies at 99% confidence, despite their similarities in M_* and SFR.

4.3. Host Galaxies

We determine stellar masses and SFRs for AGN host galaxies after subtracting the AGN component from the SED. This introduces some additional uncertainty in the resulting masses and SFRs beyond the original photometric uncertainties, as discussed in Section 3.3. The uncertainty in the AGN contribution to the measured MIR fluxes can prevent detection of low-level star formation in IR AGNs. The SFR distribution among IR AGNs is therefore biased toward high SFR.

Figure 9 shows the results of comparing galaxies hosting different types of AGNs to one another and also to cluster galaxies as a whole. The stellar mass and SFR distributions of galaxies hosting X-ray and IR AGNs show no measurable differences with the distributions of all cluster members. Merging the X-ray and IR AGN samples likewise yields no measurable difference. However, the hosts of IR AGNs have high specific SFRs (sSFR) compared to the hosts of X-ray AGNs and to all cluster members at 98% and 97% confidence, respectively. The difference between the sSFRs of X-ray AGN hosts and the full galaxy sample is not significant. However, X-ray AGN hosts appear to have lower sSFRs than the average galaxy in Figure 9, which is consistent with previous results using field galaxies (Hickox et al. 2009). We must also consider the effect of non-detections on the measured distributions. Many of the IR AGN hosts have upper limits on SFR that are smaller than the SFRs of the X-ray AGN host galaxies with the lowest measurable SFRs. Therefore, if the IR AGN hosts had a distribution of SFRs similar to the X-ray AGN hosts with measurable star-formation, star-formation would have been detected in most IR AGN hosts. This indicates that uncertainties in the AGN corrections alone cannot account for the higher sSFRs among IR AGN hosts.

The IRAC color-color diagram (e.g. Stern et al. 2005)

probes the nature of AGN host galaxies independent of their model SEDs by identifying the dominant source of their MIR emission (Donley et al. 2008). The MIR colors of X-ray and IR AGNs before their AGN components are subtracted are compared to all cluster members in Figure 6. Galaxies hosting AGNs have unremarkable $[5.8] - [8.0]$ colors but do not extend as far to the red as normal galaxies, which indicates that AGNs are seldom found in starbursts or luminous infrared galaxies (Donley et al. 2008). AGN hosts also show redder $[3.6] - [4.5]$ colors than typical for a red sequence galaxy, which may indicate a contribution of hot dust to the $4.5\mu\text{m}$ continuum. The colors of AGN hosts, especially IR AGN hosts, are influenced by the AGN continuum, but tests using the AGN and spiral galaxy templates indicate that only galaxies in the Stern wedge have more than 50% of their IRAC fluxes contributed by the AGN component. A two-dimensional KS-test confirms that, after excluding objects in the Stern wedge, the IRAC colors of both X-ray and IR AGNs differ from normal galaxies at $> 99.9\%$ confidence, and the absence of X-ray AGNs among the most vigorously star-forming galaxies (those with the reddest $[5.8] - [8.0]$ colors) is consistent with earlier indications that X-ray AGNs avoid the blue cloud in visible color-magnitude diagrams (CMDs; Schawinski et al. 2009; Hickox et al. 2009). The distribution of X-ray AGNs in Figure 6 also appears to be consistent with the results of Gorjian et al. (2008), who found that $16.8 \pm 0.3\%$ of X-ray-identified AGNs outside the Stern wedge had very red $[5.8] - [8.0]$ colors consistent with vigorous, on-going star-formation. We found this population to be $20 \pm 6\%$ among our X-ray AGNs.

The visible CMD provides a means to estimate the nature of galaxies in the absence of measurable star-formation at MIR wavelengths. Figure 10 shows the CMD for each cluster after the AGN component has been subtracted. The fraction of cluster members hosting an X-ray AGN peaks on the red sequence, and the probability that the X-ray AGN hosts are drawn from the parent cluster population is less than 10^{-3} . This contrasts with AGN hosts in the field, where the X-ray AGN fraction typically peaks in the green valley (Hickox et al. 2009; Schawinski et al. 2009; Silverman et al. 2009, henceforth S09) for AGNs identified using either X-ray luminosity or emission-line diagnostics. IR AGN hosts, both in our sample of cluster AGNs and in the field sample of Hickox et al. (2009), conspicuously avoid the red sequence. Like the difference between X-ray AGN hosts and the parent cluster population, this result is significant at $> 99.9\%$ confidence. This indicates that the IR AGN sample has at most limited contamination by MIR-excess early-type galaxies of the sort studied by, e.g. Brand et al. (2009). Galaxies hosting IR AGNs in clusters also show an important difference compared to their counterparts in the field. While only 1.5% of field galaxies hosting the IR AGNs studied by Hickox et al. (2009) had $^{0.1}(u - g)$ colors redder than the median of the red sequence, more than 20% of IR AGNs in clusters have visible colors redder than the red sequence in their parent clusters.

We examined the SDSS $g - r$ colors of very red galaxies ($((V - R)_{\text{rest-frame}} > 0.8)$ in Abell 1689, which has the largest number of such objects, and found that most also appear red in SDSS colors. The most notable exception

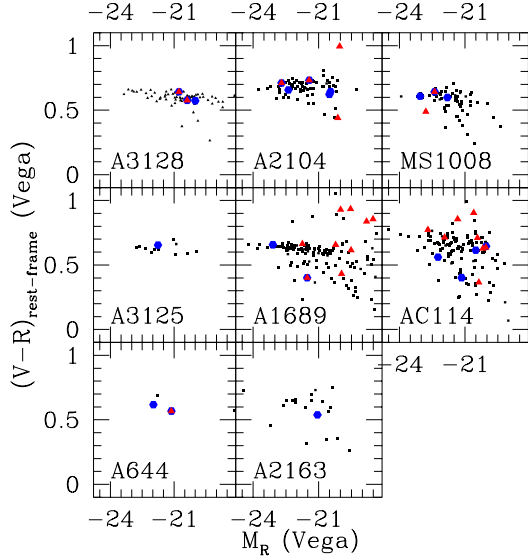


FIG. 10.— Optical color-magnitude diagrams showing the spectroscopically-confirmed member galaxies (black squares), X-ray AGNs (blue hexagons) and IR AGNs (red triangles) of each cluster. The contribution of the AGN component to the model SED has been subtracted from the IR AGNs, leaving estimated host-galaxy colors and luminosities. Typical uncertainties on colors and absolute magnitudes are approximately 0.1 mag. See Section 4.3 for further discussion.

is Abell 1689 #192, which we have identified as an IR AGN, which suggests that its colors may change due to AGN variability. The qualitative agreement between the colors of very red galaxies in Figure 10 and their $g-r$ colors from SDSS suggests that these objects are genuinely unusual and not the result of photometric errors. These galaxies also show substantial reddening of the AGN template in their A10 fit results, with $\langle E(B-V) \rangle = 0.4$ and a trend for higher $E(B-V)$ in galaxies with redder colors at 97% confidence. These results suggest that the unusually red galaxies in Figure 10 experience significant internal extinction that is not present in most galaxies.

Since the AGN component of the SED fit may account not only for a true AGN contribution but also for intrinsic variations about the normal galaxy templates, some or all of these very red AGNs, which represent approximately 1/3 of our IR AGN sample, may not be true AGNs. However, fewer than half (7/17) of objects with $(V-R)_{\text{rest-frame}} > 0.8$ are identified as IR AGNs; this implies that IR AGNs must differ from normal galaxies not only in the visible but also in the MIR, and MIR fluxes are practically immune to extinction. Therefore, most of the IR AGNs identified in this region of color-magnitude space cannot be false-positives selected due to their unusual visible colors but must have genuine nuclear activity contributing to their SEDs.

4.4. Accretion Rates

We use the bolometric luminosities of both X-ray and IR AGNs to measure the growth of their black holes and compare the black hole growth to the assembly of stellar mass in their host galaxies. The accretion rate of a black hole can be generically written as,

$$\dot{M}_{BH} = \frac{L_{bol}}{\epsilon c^2} \quad (14)$$

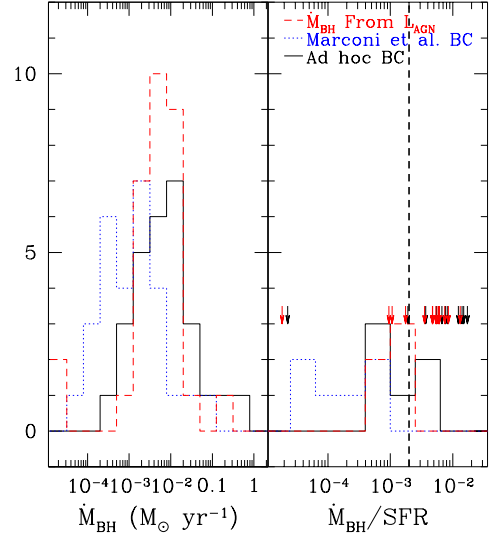


FIG. 11.— Comparison of accretion rates (\dot{M}_{BH} ; left panel) and SMBH growth rates relative to their host galaxies (\dot{M}_{BH}/SFR ; right panel). The various distributions compare different methods of estimating \dot{M}_{BH} : directly from the SEDs of IR AGNs (red dashed), applying *ad hoc* BCs derived from AGNs with both X-ray and IR identifications (solid black), and applying the M04 BCs (blue dotted). M04 BCs return significantly lower \dot{M}_{BH} than the other two methods, which are consistent with one another. Short black and red arrows mark upper limits for X-ray and IR AGNs, respectively. The dashed vertical line marks the ratio required to maintain the $z = 0$ $\dot{M}_{BH}-M_{bulge}$ relation (Marconi & Hunt 2003). See Section 4.4 for more on the various BCs.

where L_{bol} is the bolometric luminosity and ϵ is the efficiency of conversion between the rest mass energy ($\dot{M}c^2$) of the accreted material and the energy radiated by the black hole. We assume $\epsilon = 0.1$, appropriate for a thin accretion disk around an SMBH with moderate spin (Thorne 1974) and determine L_{bol} as described in Section 4.1.

The accretion rates derived from Eqn. 14 for the X-ray and IR AGN samples are shown in Figure 11. The left panel suggests that X-ray and IR AGNs have similar accretion rates, and a KS test reveals that there is no significant difference between the two samples. This is surprising, since we would naïvely expect that the difference between X-ray and IR AGNs might be due to different dependence of X-ray and IR selection techniques on luminosity. Instead, the right panel of Figure 11 shows that the X-ray and IR AGN samples have $\langle \dot{M}_{BH}/SFR \rangle = 3 \times 10^{-3}$ and $\langle \dot{M}_{BH}/SFR \rangle = 2 \times 10^{-3}$, respectively. These ratios are comparable to the mean \dot{M}_{BH}/M_{bulge} in the local universe (2×10^{-3} , Marconi & Hunt 2003), which indicates that the SMBHs in cluster AGNs are accreting at approximately the rate required to maintain the $z = 0$ $\dot{M}_{BH}-M_{bulge}$ relation. However, this is likely an artifact of our SFR detection thresholds, as the accretion rates of these objects are not large enough to produce outliers on the $\dot{M}_{BH}-M_{bulge}$ relation in a Hubble time.

Figure 12 compares black hole accretion rates with host mass and sSFR. We find no significant correlation between \dot{M}_{BH} and sSFR, nor do we find a correlation of \dot{M}_{BH} with stellar mass among the X-ray AGN sample. However, \dot{M}_{BH} correlates with stellar mass among IR

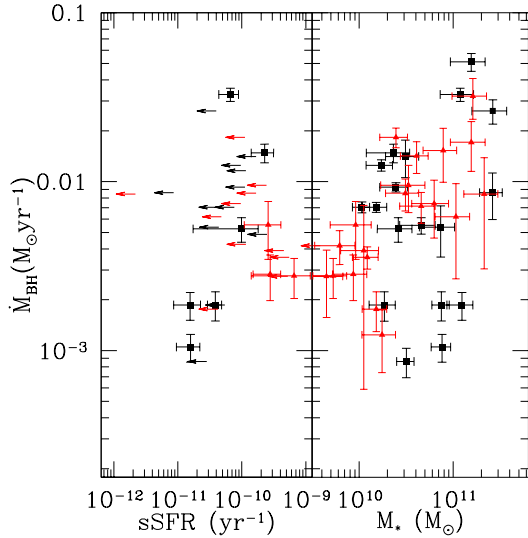


FIG. 12.— Relationships of black hole accretion rates (\dot{M}_{BH}) to stellar masses and sSFRs. Black points and arrows show \dot{M}_{BH} inferred from X-ray luminosities using BCs from Eqn. 13, while red points and arrows mark \dot{M}_{BH} inferred from integrating model SEDs. Stellar masses and SFRs are measured from SEDs and include the entire galaxy, not just the spheroidal component.

AGNs at 99.5% confidence, weakening to 98% confidence among the merged AGN sample. This correlation may be related to the ability of more massive cluster members to retain more cold gas.

Figure 13 shows the relationship between black hole growth and stellar mass assembly in AGN host galaxies. The correlation of \dot{M}_{BH} with SFR is extraordinarily strong ($> 99.9\%$ confidence), and both X-ray and IR AGNs appear to follow the same relation, with $\text{SFR} \propto \dot{M}_{BH}^{0.46 \pm 0.06}$. Netzer (2009) studied emission line selected AGNs from SDSS and also found a tight correlation between SFR and AGN luminosity across nearly 5 dex in L_{bol} . However, their $\text{SFR}-\dot{M}_{BH}$ relation ($\text{SFR} \propto \dot{M}_{BH}^{0.8}$) is steeper than ours at 5.7σ . Furthermore, Lutz et al. (2010) performed a stacking analysis of X-ray identified AGNs at $z \sim 1$ and found no measurable correlation of SFR with L_{bol} for AGNs with $L_{2-10\text{keV}} < 10^{44} \text{ erg s}^{-1}$. However, the millimeter-bright, optically luminous QSOs studied by Lutz et al. (2008) appear to be consistent with both Netzer (2009) and Lutz et al. (2010). The qualitative similarity of our results to those of Netzer (2009) and Lutz et al. (2010) suggests that we are seeing the same underlying relationship. That both X-ray, IR and emission-line selected AGNs appear to show the same general trend toward higher \dot{M}_{BH} in hosts with higher SFR suggests that accretion rates in all of these objects are set by the size of the global cold gas reservoir. Such a relationship is also predicted theoretically as a result of large-scale dynamical instabilities, which drive cold gas to the centers of galaxies where it can be accreted (Kawakatu & Wada 2008; Hopkins & Quataert 2010). However, the quantitative discrepancies between the various observational signatures of star-formation and gas accretion indicate that further work on the relationship between these phenomena is needed.

Figure 13 also compares star-formation and black hole growth among our AGN sample with the median ratio

found by S09 and the ratio needed to maintain the $z = 0$ $\dot{M}_{BH}-M_{bulge}$ relation. In some cases \dot{M}_{BH}/SFR falls more than a dex below the ratio reported by S09 for field galaxies at $z \approx 0.8$ and more than 0.3 dex below the rate needed to maintain the local $\dot{M}_{BH}-M_{bulge}$ relation. However, if we consider AGN hosts with no measurable star-formation, the disagreement in \dot{M}_{BH}/\dot{M}_* between the cluster AGNs we measure and the field AGNs of S09 becomes far less pronounced. The upper limits in Figure 13 fill in much of the empty space between the S09 median relation and the cluster AGNs with measurable star-formation, but the fraction of galaxies with $\dot{M}_{BH}/\text{SFR} < 2 \times 10^{-3}$ is larger in Figure 13 than in Figure 13 of S09 (7/39 versus 9/67). This difference grows (7/27) if we consider only AGNs with $\dot{M}_{BH} < 10^{-2} M_{\odot} \text{ yr}^{-1}$, which is below the luminosity limit of the S09 sample. However, even the difference between the low-luminosity subsample and the S09 result is not statistically significant (90% confidence). Silverman et al. (2009) project the evolution in the median SFR of their AGN sample to $z = 0$ and find that it agrees with the SFRs measured in Type 2 AGNs with $\log(L_{[OIII]}) > 40.5$ in SDSS. The median $z = 0.2$ SFR for the S09 AGN hosts is $\text{SFR} \approx 0.5 M_{\odot} \text{ yr}^{-1}$, which is comparable to our detection threshold. As a result, the AGNs measured in Figure 13 are more comparable to a high-SFR subsample of the S09 AGNs. However, there is no significant difference in the \dot{M}_{BH}/SFR of high-SFR versus low-SFR AGNs in S09. We therefore concluded that the ratio of \dot{M}_{BH} to SFR our sample of low- z cluster AGNs is consistent with the ratios observed in high- z AGNs in the field.

4.5. Radial Distributions

Martini et al. (2007) found that luminous ($L_X > 10^{42} \text{ erg s}^{-1}$) X-ray AGNs were more centrally concentrated in R/R_{200} than normal cluster members at 97% confidence. After pruning the AGN sample of suspect redshifts and applying improved K-corrections, we assemble the radial distributions of our AGN samples in Figure 14. Figures 14a and 14b, which consider the X-ray and IR AGN samples, respectively, have slightly different distributions of parent galaxies. This is because *Spitzer* pointings cover only the fields around X-ray sources identified by M06 and not the full *Chandra* field of view. The IR AGNs are selected from the cluster member catalog after SED fitting has been performed, so the radial distribution of IR AGNs is guaranteed to be unbiased with respect to the cluster galaxy sample we used above, while X-ray AGNs must be compared to the distribution of all galaxies within the *Chandra* footprint. These different selection footprints lead to the different radial distributions shown in the solid red and black lines in Figure 14b. The difference is not significant, however, and has no impact on our conclusions.

We have determined that the host galaxy of the X-ray point source identified as the cluster AGN AC114-5 by M06 had an erroneous spectroscopic redshift reported in the literature (see Section 3.1 and Figure 1). Our SED fitting indicates that this source is a background QSO at $z_{phot} \approx 0.99$. Without this object, which is located at a projected distance $R/R_{200} \approx 0.2$ from the center of AC 114, the significance of the difference between the lumi-

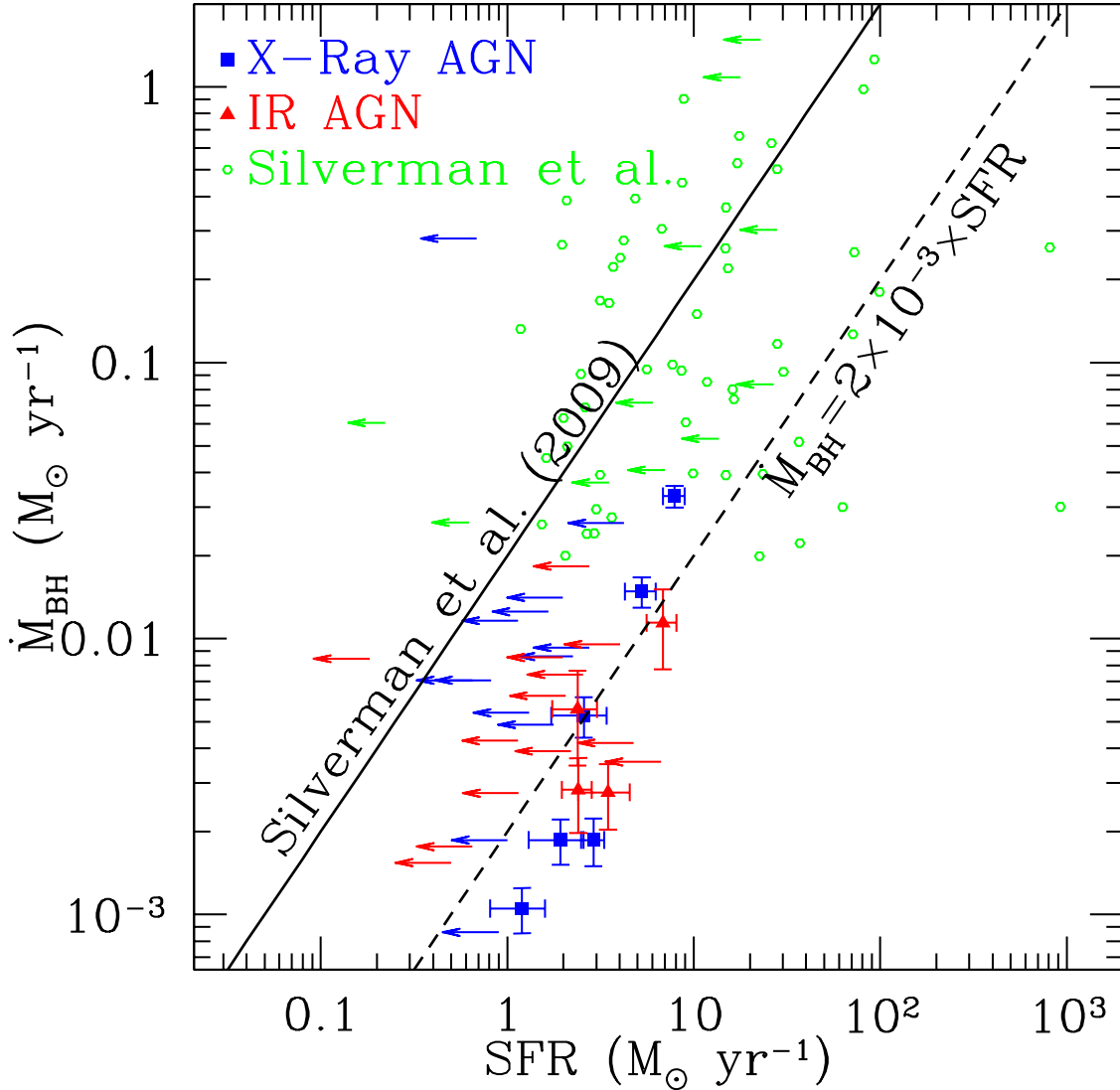


FIG. 13.— Relationship between black hole growth and star-formation in our AGN sample compared to the AGN sample from COSMOS examined by S09. Green circles and arrows mark the S09 AGNs. All other symbols are the same as in Figure 12. Lines mark the \dot{M}_{BH}/SFR relation measured by S09 (*solid*) and the ratio required to produce the $z = 0$ $M_{BH}-M_{bulge}$ relation (Marconi & Hunt 2003; *dashed*). Our SFRs and those reported by Silverman et al. (2009) are galaxy-wide SFRs rather than bulge SFRs.

nous X-ray AGN and control samples drops to 89% confidence with a luminosity-selected control sample and 92% confidence with a mass-selected control sample. Consistent with the results of Martini et al. (2007), we also find no significant difference between the radial distribution of the full X-ray AGN sample compared to the distribution of cluster members as a whole.

Following Martini et al. (2009), we also try a redshift-dependent luminosity threshold ($M_{R,cut} = M_R^*(0) + 1 - z$) in place of a fixed value. The galaxy and AGN samples selected using this criterion show no significant differences in their R/R_{200} distributions. Martini et al. (2009) chose this evolving threshold to select a sample of passively-evolving galaxies at fixed stellar mass. A mass threshold ($M_* > 3 \times 10^{10} M_\odot$) appropriate for an ellipti-

cal galaxy at $z = 0$ with $M_R = M_{R,cut}$ again yields no measurable difference between the radial distributions of X-ray AGNs and all cluster members. We conclude that the radial distributions of both X-ray and IR AGNs in galaxy clusters are consistent with the distribution of cluster members, although the agreement between cluster members and IR AGNs is much better than between cluster members and X-ray AGNs.

5. DISCUSSION

Identifying AGN from their X-ray emission is widely considered to be among the most robust means of selecting AGNs (e.g. Ueda et al. 2003, S09, A10), because the measured hard X-ray luminosity of a given AGN is largely insensitive to absorption if $N_H < 10^{24} \text{ cm}^{-2}$. Furthermore, the fraction of Compton-thick AGNs ($N_H > 10^{24} \text{ cm}^{-2}$) is small, with 10% or less of all cosmic black hole growth taking place in Compton-thick systems

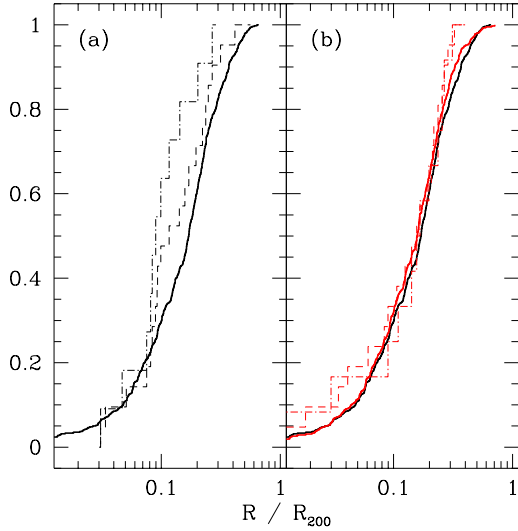


FIG. 14.— Distributions of X-ray AGNs, IR AGNs and all cluster galaxies within their parent clusters. *Panel a:* luminous ($L_X > 10^{42}$ erg s $^{-1}$; dot-dashed) and all X-ray AGNs (dashed) compared to all cluster members with $M_* > M_{\text{cut}} = 3 \times 10^{10} M_\odot$ (solid). *Panel b:* luminous ($L_{\text{bol}} > 10^{10} L_\odot$; dot-dashed red) and all IR AGNs (dashed red) compared to cluster members with *Spitzer* coverage and $M_* > M_{\text{cut}}$ (solid red) and the unbiased sample of galaxies inside the *Chandra* footprint (solid black).

(Treister et al. 2009). Alternatively, AGNs can also be robustly identified from their UV continuum emission after it has been absorbed by dust and re-emitted in the MIR. If these techniques are similarly immune to the effects of absorption they should yield very similar AGN samples. Instead, we find that at most 15% of AGNs in galaxy clusters are identified by both X-ray and MIR techniques.

Furthermore, it is clear that this dichotomy does not result solely from the relative luminosities of X-ray and IR AGNs. The IR AGN sample contains 5-9 objects that should have been detected in X-rays if their SEDs were similar to those AGNs identified using both selection methods. The most prominent of these is Abell 1689 #109, which has $L_{\text{bol}} \approx 8 \times 10^{45}$ erg s $^{-1}$ but was not detected in the *Chandra* image used by M06 to identify X-ray AGNs in Abell 1689. This AGN appears quite prominently in a subsequent *Chandra* image, indicating that its initial non-detection was most likely the result of X-ray variability. This example demonstrates that the absence of detectable X-ray emission from an AGN candidate, even a fairly luminous one, does not necessarily preclude the presence of an AGN. However, Abell 1689 #109 is not typical. The IR AGNs with significant X-ray non-detections are not necessarily the most luminous. Instead, they reside in the clusters with the deepest X-ray images. Indeed, all of the X-ray non-detections in AC 114 that fall within the *Chandra* image footprint are predicted to be at least 3 times brighter than the faintest reported X-ray point source. As a result, at least some of these non-detections could indicate contamination of the IR AGN sample by one or more of the effects discussed in Section 3.2, e.g. intrinsic variation in the AGN SED or dust heating by AGB carbon-stars. More observational and theoretical work on the dust emission in old stellar populations are required before the potential of these

sources of MIR emission to mimic an AGN-like SED can be quantified.

In the absence of detailed, calibrated models for “contamination” of MIR emission by old stars, we assume that this component is negligible. This implies that X-ray selection alone can miss a large fraction of moderate-to-low luminosity AGNs. This could have important implications for studies of star-formation in clusters using MIR luminosities (e.g. Saintonge et al. 2008; Bai et al. 2009; Geach et al. 2009). This is especially important if authors assume that AGNs can always be identified with X-rays alone or that the MIR emission from galaxies with X-ray excesses is always dominated by AGN emission. These assumptions imply that any MIR emission not associated with an X-ray AGN must be powered by star-formation and that no MIR emission from a galaxy hosting an X-ray AGN can be powered by star-formation. Our results indicate that these assumptions may lead authors to overestimate the number of cluster galaxies with vigorous star-formation and to underestimate the number with moderate star-formation. Therefore, additional tests for AGN are needed to correctly interpret the MIR luminosities of cluster galaxies.

A difference between X-ray- and MIR-selected AGN samples also appears among field samples, which consist of more luminous AGNs than the ones we study and use a different MIR selection method (Hickox et al. 2009). The color distributions of IR AGNs selected using different techniques also differ from one another, but it is clear that galaxies hosting AGNs identified from their X-ray emission are dissimilar from galaxies hosting AGNs identified in the MIR. Most notably, IR AGN hosts have significantly higher sSFRs than the average cluster galaxy, while there is no significant difference between the sSFRs of X-ray AGNs and the cluster population as a whole. Since SFR correlates well with cold gas mass, higher sSFRs among IR AGN host galaxies suggests these galaxies have a larger fraction of their baryons in cold gas than X-ray AGN hosts. However, the differences discussed in Section 4.3 are determined only for galaxies with measurable star-formation. Several IR AGNs are found in host galaxies that have both visible and IRAC colors consistent with passively-evolving stellar systems.

The tight correlations between accretion rates of both X-ray and IR AGNs with SFR in their host galaxies suggests that the two classes are fueled by the same mechanism and are therefore fundamentally similar. Subject to the caveat described above, the larger sSFRs found in IR AGN hosts might explain the apparent dichotomy of the two AGN classes despite their physical similarity. Larger gas fractions in IR AGN hosts could lead to larger average column densities in IR AGNs, depressing L_X/L_{bol} in these systems. The presence of at least 5 of the 8 IR AGNs with X-ray counterparts on the red sequence, where there is little cold gas to participate in X-ray absorption, tends to support this scenario (Figure 10). If cold gas fractions of AGN host galaxies influence the detectability of X-ray AGNs, this might also explain the dearth of X-ray AGNs in the green valley in clusters compared to the field. The X-ray AGNs in our sample are weaker than the AGNs usually studied in field galaxy samples, and a modest cold gas reservoir in green valley galaxies could more easily absorb enough X-rays from an AGN with $L_X = 10^{41}$ erg s $^{-1}$ to make it undetectable.

Doing the same for an AGN with $L_X = 10^{43} \text{ erg s}^{-1}$, which is more typical for the field samples studied by, e.g. Hickox et al. (2009) and S09, would require a larger gas column.

Just over half (58%) of the M06 X-ray point sources have detectable hard X-ray emission, and therefore many AGNs near the *Chandra* detection limits could be hidden by a sufficiently large absorbing column. Only 3 of the 9 IR AGNs in AC114 whose bolometric luminosities imply that they should have been detected in X-rays, but were not, would remain detectable in the soft X-ray band behind a gas column with $N_H = 10^{22} \text{ cm}^{-2}$. This column density is large for Type I AGNs, but it is not unusual for Type II AGNs observed in X-rays (Ueda et al. 2003). Furthermore, X-ray and IR AGNs seem to obey the same relationship between SFR and accretion rate in AGN hosts whose SFRs are measurable. This is consistent with the hypothesis that the apparent dichotomy between X-ray and IR AGNs is false, and the shape of an AGN's SED depends strongly on the amount of absorbing material between us and the central black hole.

The scenario we propose, in which absorption by cold gas in the host galaxy is responsible for the absence of detectable X-ray emission from IR AGNs, is consistent with the differences we find between the two samples. However, verifying that absorption by the host ISM is indeed the cause of this observed difference will require deeper X-ray observations to detect X-ray counterparts and estimate absorption columns. If this can be accomplished, the presence of spectral signatures of X-ray absorption would confirm that the host galaxy is responsible for hiding some IR AGNs from X-ray detection.

6. CONCLUSIONS

We have used *Spitzer* imaging of galaxy clusters to identify AGNs and to measure the masses and star-formation rates of their host galaxies. We find that AGNs identified by this technique have very little overlap with AGNs identified in X-rays. We compared the host galaxies of AGNs identified using the two methods and determined that, while their masses and SFRs are indistinguishable, IR AGNs reside in galaxies with higher sSFRs than both X-ray AGN hosts and the parent sample of cluster galaxies. The hosts of X-ray AGNs have sSFRs that are somewhat lower than but consistent with the sSFRs seen in cluster galaxies as a whole. The difference between X-ray AGN hosts and normal cluster galaxies is significant only when comparing their positions in visible color-magnitude and MIR color-color diagrams. X-ray AGN hosts are rarely found in the regions of both diagrams associated with vigorous star-formation.

We also find that accretion rates of both X-ray and IR AGNs correlate strongly with SFR in their host galaxies. This suggests that X-ray and IR AGNs are physically similar and are fueled by the same mechanism. We hypothesize that the larger sSFRs seen in IR AGN hosts indicate larger cold gas fractions in these galaxies, and sug-

gest that this could account for the apparent dichotomy between X-ray and IR AGNs. A moderately large cold gas column density of 10^{23} cm^{-2} could suppress the X-ray emission from the IR AGNs enough that we would be unable to detect them. The presence of IR AGNs but not X-ray AGNs in galaxies with very red optical colors, indicative of strong absorption, lends credence to this hypothesis. It might also be verifiable directly by deep X-ray observations of either AC 114 or Abell 1689 to search for X-ray emission from IR AGNs and to determine if such X-ray emission shows evidence for absorption intrinsic to the host galaxy. For example, the most luminous IR AGN with no X-ray counterpart in Abell 1689 could be detected by *Chandra* with S/N = 3 per resolution element at 4 keV—the energy cutoff for objects with $N_H = 10^{23} \text{ cm}^{-2}$ —in 160 ks. This would allow a crude model spectrum to be constructed and the intrinsic absorption column to be measured. Finally, we have obtained NIR spectra of several IR AGN in Abell 1689, which we will examine for high-ionization emission lines that would unambiguously indicate the presence of an AGN.

Following Martini et al. (2007), we compared the radial distributions of AGNs and all cluster members. We eliminated one AGN with a spectroscopic redshift from the literature that incorrectly identified a background quasar as a cluster member. Without this object, the significance of their result that luminous X-ray AGNs ($L_X > 10^{42} \text{ erg s}^{-1}$) are more concentrated than cluster members as a whole is reduced to $\sim 90\%$ confidence. While this result is no longer significant, it would be worthwhile to extend the present sample using archival *Chandra* imaging of additional clusters to either confirm or refute that X-ray luminous AGNs are more concentrated than the galaxy populations of their parent clusters. It is unlikely, however, that a similar exercise using IR AGNs would yield a positive result, as the radial distribution of IR AGNs agrees very closely with the distribution of cluster galaxies.

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TABLE 1
CLUSTER SAMPLE

Cluster	z	σ_v (km s ⁻¹)	N_{members}	IRAC AOR(s)	$\nu L_{\nu, \text{obs}}(8\mu\text{m})$ Limit (10 ⁴² erg s ⁻¹)	MIPS AOR(s)	$\nu L_{\nu, \text{obs}}(24\mu\text{m})$ Limit (10 ⁴¹ erg s ⁻¹)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Abell 3128	0.0595	906	83	25410816	0.54	25411072	2.6
Abell 3125	0.0616	475	25	25409792	0.58	25410048	2.6
Abell 644	0.0701	952	9	25409280	1.0	—	—
Abell 2104	0.1544	1242	74	25411328	1.2	25411584	1.9
Abell 1689	0.1867	1400	160	4754176, 14696192, 14696448, 14696704, 14696960, 14697216, 14697472, 25411840	1.3	4770048, 4769792, 19042304, 19042048	2.8
Abell 2163	0.2007	1381	27	25412352	1.8	25412608	3.4
MS 1008.1-1224	0.3068	1127	68	25410304	0.81	—	—
AC 114	0.3148	1388	159	4756480, 12653824, 25412864	1.0	4773888, 4774144, 25413120	2.2

NOTE. — Summary of clusters included in the analysis and the observations contributing to the MIR mosaic images of each cluster. The extra line beneath Abell 1689 contains additional AORs that do not fit on a single line. (1) Redshifts from Martini et al. (2007), determined using the biweight estimator of Beers et al. (1990). (2) Velocity dispersions of cluster members estimated by Martini et al. (2009) using the biweight measure of Beers et al. (1990). (3) Total number of galaxies with both MIR and *R*-band coverage identified as cluster members by Martini et al. (2007) or extracted from the literature using their redshift limits. (4) Astronomical Observation Request (AOR) numbers of Spitzer observations used to construct IRAC mosaics. (5) The minimum detectable observer-frame $8\mu\text{m}$ luminosity in each cluster, derived from the 3σ lower limit on measurable flux in a “typical” part of the $8\mu\text{m}$ mosaic image. Due to the variable coverage across the cluster, lower luminosities are detectable in some cluster members than in others. (6) AORs used to construct the $24\mu\text{m}$ mosaics. (7) 3σ lower limits on detectable $24\mu\text{m}$ luminosities. These are derived in a similar manner to the IRAC limits in column (5) and have the same caveats.

TABLE 2
CLUSTER MEMBER PHOTOMETRY

Name	RA	Dec	B	V	R	I	$F_\nu(3.6\mu\text{m})$ (mJy)	$F_\nu(4.5\mu\text{m})$ (mJy)	$F_\nu(5.8\mu\text{m})$ (mJy)	$F_\nu(8.0\mu\text{m})$ (mJy)	$F_\nu(24\mu\text{m})$ (mJy)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
a3128-001	03:30:37.7	-52:32:57	17.88 ± 0.08	16.81 ± 0.06	16.21 ± 0.06	—	1.37 ± 0.08	0.90 ± 0.08	0.66 ± 0.17	< 0.77	< 0.84
a3125-001	03:27:20.2	-53:28:34	17.87 ± 0.12	16.89 ± 0.09	16.29 ± 0.09	—	—	1.37 ± 0.14	—	9.49 ± 0.85	8.68 ± 2.28
a644-011	08:17:39.5	-07:33:09	17.29 ± 0.12	16.69 ± 0.09	16.20 ± 0.09	—	2.61 ± 0.21	2.55 ± 0.24	3.62 ± 0.48	5.15 ± 0.62	—
a2104-001	15:40:07.6	-03:17:06	20.59 ± 0.16	19.34 ± 0.12	18.62 ± 0.12	18.05 ± 0.11	0.18 ± 0.02	0.13 ± 0.01	< 0.08	< 0.19	< 0.07
a1689-004	13:11:29.5	-01:20:27	17.87 ± 0.14	16.48 ± 0.10	15.75 ± 0.10	15.16 ± 0.09	2.89 ± 0.26	2.11 ± 0.19	1.21 ± 0.11	0.87 ± 0.08	< 0.29
a2163-001	16:15:25.8	-06:09:26	20.70 ± 0.19	19.69 ± 0.16	18.88 ± 0.14	—	0.10 ± 0.01	0.08 ± 0.01	< 0.07	< 0.21	< 0.10
ms1008-001	10:10:34.1	-12:39:52	22.58 ± 0.12	21.11 ± 0.09	20.10 ± 0.08	19.41 ± 0.08	0.08 ± 0.01	0.07 ± 0.01	0.04 ± 0.01	< 0.05	—
ac114-001	22:58:52.3	-34:46:47	—	22.40 ± 0.12	21.73 ± 0.10	21.40 ± 0.11	0.00 ± 0.00	0.00 ± 0.00	< 0.01	< 0.02	—

NOTE. — Visible and MIR photometry for a small selection of example galaxies. The full table is available from the online version of the journal. (1) The name of this object, constructed from a shorthand of its parent cluster and the order in which each object appears in the list of cluster members extracted from NED. (2-3) Positions of this object in J2000 coordinates, as derived from the *R*-band images. (4-7) Visible photometry for each object, where detectable, in Vega magnitudes. Fluxes are measured in the *R*-band Kron-like aperture. Objects with no quoted magnitudes in a given band have either no coverage or no detection in that band. No upper limits are quoted. (5-8) MIR fluxes measured in *R*-band Kron-like aperture. Where appropriate, 3σ upper limits on measured MIR fluxes, derived from the appropriate uncertainty mosaic, are given. Galaxies with no quoted upper limit for a given band have no coverage in the corresponding image.

TABLE 1
IDENTIFIED ACTIVE GALACTIC NUCLEI

Name (1)	Martini Name (2)	RA (3)	Dec (4)	$L_{bol}(10^{43} \text{ erg s}^{-1})$ (5)	$L_X (10^{41} \text{ erg s}^{-1})$ (6)	$M_*(10^{10} M_\odot)$ (7)	SFR ($M_\odot \text{ yr}^{-1}$) (8)
a3128-004	a3128-9	03:30:39.3	-52:32:05	1.5 ± 0.5	3.8	$3.2 \pm 0.9(\text{stat}) \pm 1.9(\text{syst})$	< 0.04
a3128-012	a3128-6	03:30:17.3	-52:34:08	1.0 ± 0.3	22.4	$1.9 \pm 0.6(\text{stat}) \pm 1.1(\text{syst})$	< 0.35
a3128-092	a3128-2	03:29:41.4	-52:29:35	—	22.4	$1.1 \pm 0.2(\text{stat}) \pm 0.6(\text{syst})$	< 0.44
a3125-044	a3125-5	03:27:05.0	-53:21:41	—	7.2	$7.5 \pm 1.6(\text{stat}) \pm 4.5(\text{syst})$	2.7 ± 0.4
a644-011	a644-1	08:17:39.5	-07:33:09	10.4 ± 1.4	28.2	$2.6 \pm 0.9(\text{stat}) \pm 1.6(\text{syst})$	< 1.38
a644-024	a644-2	08:17:48.1	-07:37:31	—	4.5	$7.6 \pm 1.8(\text{stat}) \pm 4.5(\text{syst})$	1.2 ± 0.4
a2104-024	a2104-4	15:40:14.0	-03:17:03	—	7.2	$2.0 \pm 0.6(\text{stat}) \pm 1.2(\text{syst})$	< 0.50
a2104-040	a2104-6	15:40:03.9	-03:20:38	—	7.2	$12.4 \pm 3.8(\text{stat}) \pm 7.4(\text{syst})$	1.9 ± 0.6
a2104-046	a2104-5	15:40:19.5	-03:18:24	—	36.3	$1.7 \pm 0.5(\text{stat}) \pm 1.0(\text{syst})$	< 0.83
a2104-051	a2104-2	15:40:16.7	-03:15:07	4.1 ± 0.8	18.2	< 2.3	< 16300.00

NOTE. — Brief sample table summarizing AGNs identified either by their X-ray luminosity or their SED shapes. The full table is available from the electronic edition of the journal. (1) The name of this object in Table ?? . (2) The name given to the X-ray source by Martini et al. (2006). (3-4) Position of this AGN in J2000 coordinates, as derived from the R -band image. (5) The bolometric luminosity derived by integrating the direct component of the AGN contribution to the model SED. These luminosities are quoted only for IR AGNs. (6) Rest-frame X-ray luminosities in the 0.3-8 keV band from Table 4 of Martini et al. (2006). X-ray luminosities are given only for X-ray AGNs. (7) Stellar mass derived using the M/L coefficients appropriate for a solar metallicity galaxy with a scaled Salpeter IMF and applying the Bruzual & Charlot population synthesis model (Bell & de Jong 2001, Table 4). Systematic errors are derived by applying the M/L coefficients appropriate for a Salpeter IMF and the PÉGASE population synthesis model. Upper limits are given at 3σ of the statistical error only. (8) SFR derived either from the $8\mu\text{m}$ luminosity, the $24\mu\text{m}$ luminosity or by taking the geometric mean of the two, depending on the measurements available. Uncertainties include only statistical errors, and upper limits are quoted at 3σ in the more sensitive of the $8\mu\text{m}$ and $24\mu\text{m}$ bands.

TABLE 2
IR AGN SELECTION EFFICIENCY

$E(B - V)$	$L_{AGN} : -100 \rightarrow -1.0$	$-1.0 \rightarrow -0.4$	$-0.4 \rightarrow 0.2$	$0.2 \rightarrow 0.8$	$0.8 \rightarrow 1.5$	$1.5 \rightarrow 100$
0–0.075	$6.9 \pm 0.3\%$	$8.1 \pm 0.3\%$	$17.8 \pm 0.4\%$	$45.5 \pm 0.9\%$	$72.9 \pm 1.9\%$	$83.8 \pm 4.6\%$
0.075–0.15	$7.0 \pm 0.4\%$	$8.3 \pm 0.3\%$	$17.8 \pm 0.4\%$	$45.6 \pm 0.6\%$	$75.5 \pm 2.0\%$	$83.8 \pm 5.0\%$
0.15–0.3	$7.0 \pm 0.3\%$	$8.3 \pm 0.3\%$	$17.1 \pm 0.4\%$	$44.7 \pm 0.8\%$	$74.2 \pm 1.7\%$	$84.3 \pm 4.2\%$
0.3–0.4	$6.7 \pm 0.5\%$	$7.5 \pm 0.4\%$	$18.2 \pm 0.6\%$	$46.2 \pm 1.3\%$	$77.2 \pm 2.7\%$	$86.8 \pm 6.9\%$
0.4–0.6	$7.2 \pm 0.4\%$	8.4 ± 0.3	$17.8 \pm 0.5\%$	$49.2 \pm 1.0\%$	$77.0 \pm 2.1\%$	$85.8 \pm 5.1\%$
0.6–1.0	$7.2 \pm 0.4\%$	$8.4 \pm 0.3\%$	$17.8 \pm 0.5\%$	$49.2 \pm 1.0\%$	$77.0 \pm 2.1\%$	$85.8 \pm 5.1\%$
1.0–2.0	$6.7 \pm 0.5\%$	$7.9 \pm 0.3\%$	$17.4 \pm 0.5\%$	$47.8 \pm 1.1\%$	$76.2 \pm 2.2\%$	$84.1 \pm 5.6\%$
2.0–100	$6.8 \pm 0.7\%$	$7.1 \pm 0.6\%$	$14.2 \pm 0.7\%$	$37.2 \pm 1.6\%$	$65.4 \pm 3.4\%$	$83.1 \pm 9.9\%$

NOTE. — Breakdown of AGN selection efficiency by $\log[L_{AGN}/10^{10} L_\odot]$ and $E(B - V)$. Efficiencies were determined using Monte Carlo to generate model SEDs with varying contributions from the three normal galaxy templates, add AGN components to the model SED, and introduce photometric errors. See § 3.2 for further details.